# Source-Side Control of AC Microgrids with Hybrid Renewable Energy Integration: A Comprehensive Review

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***Abstract:***

With renewable distributed energy sources consisting of solar, wind, biomass, and small hydro becoming considerably prevalent, microgrids are evolving as eco-friendly, decentralized power systems. AC microgrids, being grid-compatible and offering freedom of expansion and reliability, have thus become the preferred platform for the integration of HRES. Nonetheless, weather-induced intermittency and variability in renewables form the fundamental challenges on ensuring voltage stability, frequency regulation, and power quality. This review paper offers a comprehensive discussion on source-side control strategies for AC microgrids comprising droop control, model predictive control, adaptive and AI-based algorithms, and hierarchical control methods. More emphasis is placed on advanced inverter control methods that ensure seamless operations in grid-connected as well as islanded mode. The hybridization and energy storage systems to enhance supply reliability and efficiency are also discussed. The critical challenges of grid synchronization, cyber threats, mode-switching, and high implementation cost are brought to the forefront. Also described are the recent approaches to power quality improvement, harmonic mitigation, load-sharing mechanisms, and their constraints in practical applications. By presenting the current panoramic view and delineating research gaps, this paper distinctly advocates the need for intelligent, resilient, and adaptive control methods for the renewable energy-rich microgrids of tomorrow. The paper concludes by venturing into possible approaches toward integrating machine learning, predictive modeling, and go-to robust

***Keywords:*** *Microgrids, Renewable Distributed Energy Sources, Hybrid Energy Systems, Source-Side Control, Power Quality, Artificial Intelligence*

## I. INTRODUCTION

The ever-growing global thirst for electricity, paired with the imperatives of climate change, has fast-tracked the intrusion of R-DESs, such as solar PV, wind turbines, biomass, and small hydro systems. Centralized-type grids have depended so much on fossil fuels, thus making them environmentally unsustainable and highly vulnerable to destabilization caused by transmission losses and increased load demand [1]. In this regard, microgrids have risen to stay as an important paradigm of the new-age power systems consisting of localized, self-sufficient energy systems working toward distributed generation, storage units, and controllable loads [2]. Figure 1describes schematic diagram of a microgrid.

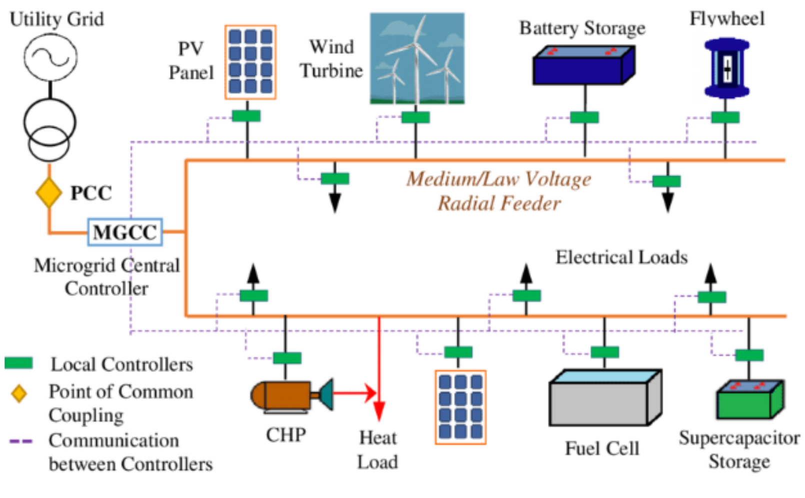


**Figure 1: Schematic diagram of a Microgrid**

A microgrid is a fantastic solution that contributes to reliability, resilience, and flexibility, as it can operate grid-tied or islanded and may, therefore, be considered a type of distributed generation (DG) or autonomous generation [3]. Within this paradigm, AC microgrids have arrived at center stage due to their compatibility with existing infrastructures, ease of integration with conventional utility grids, and maturity with respect to standards and technology adoption [4]. Modular by nature, they typically host DERs and ESS within a scheme inter-connected by AC bus lines and hierarchical control structures such as voltage control, frequency control, or economic dispatch [5]. Anarray of applications exist for AC Microgrids in rural electrification, industrial clusters, smart cities, military installations, and disaster recovery [6].

Nevertheless, the intermittency and variability of such resources greatly pose thick operational problems. Solar and wind, for example, are weather-dependent and mostly unpredictable, thus power frequently fluctuates [7]. To overcome such problems, the concept of hybrid systems came to existence where a couple of renewable resources and conversion and storage technologies are combined to ensure that such culture had continuous and stable power out-put. Solar and wind resources have such an occurrence of complementarities-natural solar production peaks in the afternoon, while the wind picks up more often at night-so they're making better use of the available resources [8]. And on the other hand, the ESSs are enhancing the reliability of the supply by compensating the fluctuations, improving the power quality, and supporting the load during peak hours [9].

Source-side control is an essential component in the reliable operation of an AC microgrid with heavy penetration of renewables. It covers everything at the generation side, including control of voltage, frequency, real power, and reactive power flow. Until recently, droop control methods were the most popular, giving decentralized capacity sharing with almost no communication [10]. However, with advanced penetration of renewable energy sources and nonlinear load conditions, the trends show an inclination towards MPC, fuzzy logic, adaptive controllers, and AI-based techniques [11]. These methods maintain stability in near real time in both grid-connected and islanded modes by improving their adaptability in real time, enhancing power-sharing accuracy, and reducing the total harmonic distortion (THD) level [12].

There are several challenges that need to be addressed, even after great technological advancements. Synchronization to the grid remains difficult due to different input characteristics generated by different DERs [13]. Threats to cyber security have increased because of high degrees of digitalization within microgrid controls, where false signals, energy thefts, or system disturbances could take place [14]. Furthermore, the reliance on ESS raises concerns regarding the costs, degradation, and sustainability of its lifeline [15]. To counter these, intelligent control architecture and adaptive control infrastructure are required. Such solutions would integrate renewables optimally when accounting for security and economy. Figure 2 describes hybrid renewable energy systems.

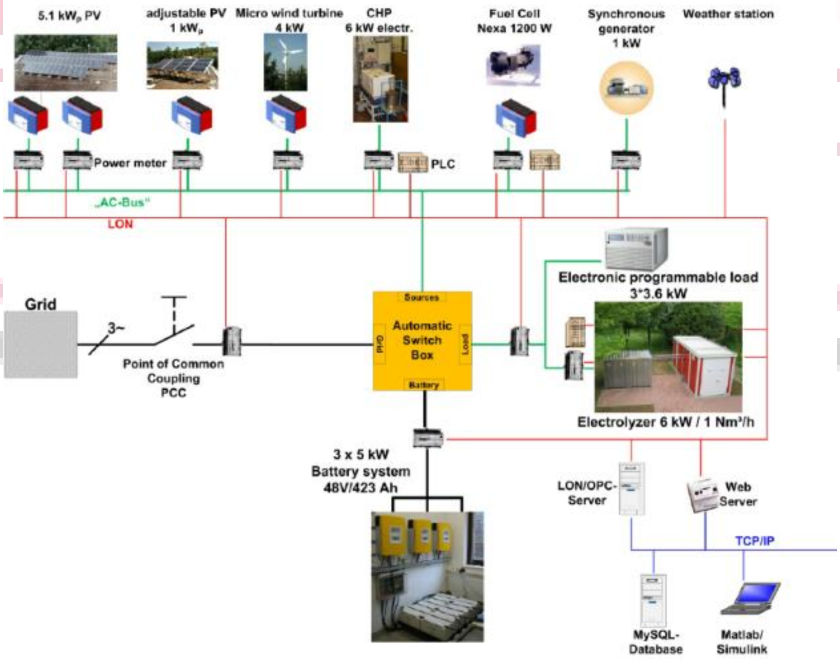


**Figure 2: Hybrid Renewable Energy Systems**

This paper reviews and consolidates state-of-the-art developments in source-side control for AC microgrids with hybrid renewable integration. It critically examines existing methodologies and present their practical limitations and research gaps. Lastly, it presents possible future research directions in AI-driven predictive control, robust communication frameworks, and cooperating operation strategies for enabling sustainable, secure, and cost-effective microgrid operation.

## II. SOURCE-SIDE CONTROL STRATEGIES IN MICROGRIDS

To further improve the source-side control of AC microgrids, a hybrid adaptive PI controller was proposed that integrated droop control and virtual impedance control. The use of artificial neural networks to adaptively tune the PI controller gains led to enhancements in voltage regulation, power sharing, and total harmonic distortion (THD) as per the IEEE-519 standards. The controller's performance was evaluated primarily through simulations and smaller testbeds, but real-time, larger-scale testing continues to be elusive, primarily due to computational overheads [1].

Adaptive droop control underpinned by system identification significantly improved the microgrid inverter performance. While it optimized transient response and small-signal stability enhancement under operating point changes, it did so by fine-tuning droop parameters through online adaptation. Improvements related to model inaccuracies, communication delays, and resilience in the presence of noise or cyber-induced disturbances remained unaddressed [2].

The power-sharing transient phase was the focus of another methodology, which attempted to guarantee that inverter-based DGs could share abrupt load increments effectively. By doing so, it avoided the overloading of single inverters [3], which, in turn, sustained system stability. Precise parameter tuning and required coordination limited this approach, and the adaptability of this method for different inverter systems with various ratings was, however, not fully explored [3].

Additional modifications to the traditional droop and virtual impedance approaches were made to try to eliminate the interdependence between active and reactive power while trying to minimize the error in load sharing. This was accomplished without the use of communication networks. The modifications made to these methods improved the overall efficiency of the system, which made their performance in unbalanced network scenarios with high levels of renewable energy integration inadequate [4].

Fixed-switching-frequency MPC improved dynamic regulation, current tracking accuracy, and switching frequency stability, and these MPC methods were used in inverter systems. Still, as with most MPC-related techniques, their application in multi-inverter systems operating in the presence of communication delays, owing to the high computational requirements and reliance on fast solvers, is not scalable [5].

More recently, distributed MPC frameworks have been put forward for the control of microgrid frequency, where distributed nodes optimize their operation in a collaborative manner subject to local constraints. Collaboration among nodes enabled asynchronous operation, enhanced system resilience, and improved fault recovery. Deployment in practice depends on the existence of efficient peer-to-peer communication infrastructure, which is lacking, as well as unresolved challenges related to synchronization errors, packet loss, and cybersecurity attacks, among others [6].

**Table 1: Source-Side Control Strategies in Microgrids**

| Ref | Contribution / Approach | Advantages / Findings | Limitation(s) |
|---|---|---|---|
| [1] | Hybrid ANN-based adaptive PI controller with droop control and virtual impedance | Improved voltage regulation, accurate power sharing, reduced THD within IEEE-519 standards | Validated mainly via simulations; large-scale real-time implementation and ANN computational overhead not addressed |
| [2] | Adaptive droop control using Narendra’s model | Enhanced transient response and small-signal stability under variable conditions | Sensitive to model inaccuracies and communication delays; robustness against noise/cyber-delays unexplored |
| [3] | Controllable transient power-sharing for inverter-based DGs | Prevented inverter overloading, improved stability during disturbances | Requires precise tuning and coordination; limited validation in heterogeneous inverter setups |
| [4] | Review of droop and virtual impedance methods | Enhanced load-sharing accuracy, reduced P/Q coupling without communication | Limited testing under unbalanced grid conditions and high renewable penetration |
| [5] | Fixed-Switching-Frequency Model Predictive Control (FSF-MPC) for coordinated inverters | Improved dynamic regulation, constant switching frequency, accurate current tracking | High computational demand, scalability issues in multi-inverter systems with delays |
| [6] | Distributed Model Predictive Control (DMPC) for frequency regulation | Improved resilience, distributed control without central coordination | Dependent on reliable peer-to-peer communication; packet loss, sync errors, cyberattacks not addressed |

## III. VOLTAGE AND FREQUENCY CONTROL

For remote microgrids, parallel inverters greatly improve system reliability and efficiency. However, the constant changes in wind and solar power create challenges for their control. A new adaptive virtual-impedance droop control scheme for parallel inverters was developed to address these challenges. Using only local data, it was able to improve reactive power sharing and lower circulating currents; however, its performance under unbalanced and noisy conditions is still unresolved [7]. The hybrid robust MPC and adaptable droop droop gains optimization framework for microgrid operations has been shown to improve renewable penetration and reduce the use of conventional energies; however, the validation for large scale real-time operation is still absent [8]. A cascaded I-P–PDN controller was developed to tackle the frequency issues of systems comprising PV, wind, EVs, and storage. It enhanced frequency performance and introduced EVs as a supple storage source. However, the analysis was for the most part simulation-based, with little attention to hardware limitations [9]. To improve the resilience of the grid, an MPC-based framework for voltage and frequency support was proposed, dealing with cold starts and transitions, such as islanding. But the solution requires an advanced computation and, in addition, has latency-ridden communication [10]. While an iterative learning control-based adaptive bidirectional droop approach was adopted for hybrid AC–DC microgrids, showcasing effectiveness in balancing AC/DC regulation, testing remained only in simulation and no tests were performed in the field or for robustness against measurement noise [11]. A newer control approach for DC–AC microgrids enhanced the mitigation of harmonics and the performance of inverter clusters; however, its development was focused on simulations and small-scale experiments [12]. The issue of sags, swells, harmonics, and transients was effectively tackled in pilot tests through a hybrid AI and semiconductor framework; however, the adoption of this technology in extensive deployments is lacking [13]. With the aid of nature-inspired optimization, a robust active power filter was constructed and demonstrated the reduction of harmonic distortion and improvement of stability, but the issue of sensitivity to parameter drift in real-world conditions is still a concern [14]. The improved voltage profiles and harmonic distortion achieved through the strategic placement of UPQC devices was a significant improvement, but the exhaustive search to locate the devices becomes computationally expensive in large networks [15]. An evaluation of filters, converters, and control methods was performed in relation to harmonic mitigation in systems with high RES, demonstrating the various trade-offs in cost and performance, but there was very little experimental validation [16]. An integrated active filter for nonlinear loads was proposed and is able to improve power quality, but how it performs during weak grid conditions or large disturbances is still unknown [17]. An ANN-based MPPT alongside multilevel inverter filters was implemented for EV charging microgrids, refining energy flows and harmonic suppression, but overly simplistic fleet models restrict applicability [18]. A DSP-based controller was developed for bidirectional storage converters tied to UPQC, alleviating harmonics and sags, although data on long-term performance is unavailable [19]. Grid-forming active power filters were introduced to a grid to actively regulate voltages and frequencies as well as suppress harmonics, yielding decent simulation results; however, these systems have not been verified in large-scale implementations [20]. A GRU-based controller for the UPQC was implemented and proved useful in quickly compensating tracked disturbances, but events that deviate from prior knowledge necessitate retraining and additional evaluation [21]. The model-free predictive control developed for UPQC was able to address transients faster than finite-set MPC, but specialized computing equipment and elevated computational costs are required [22]. The use of hybrid storage and control coordination in EV charging substations also lowered the THD and enhanced the voltage stability, though a complete assessment of the impacts at the feeder level was not performed [23].A LMS-based adaptive switching controller for the PV-fed UPQC was able to improve the PQ indices in the simulations, but the ANN training dataset influenced unusual fault detection and demonstrated a lack of robustness [24]. Lastly, with the aim of exploring the recently published advancements, the event-triggered control, hybrid UPQC/APF configurations, and ML-based control were compiled particularly to expose challenges, but none of the proposed solutions were tested [25]. [26] Highlighted the effectiveness of advanced compensators in enhancing stability, though large-scale validations and integration with diverse microgrid architectures remain future challenges..

**Table 2: Voltage/Frequency Control and Power Quality Improvement**

| Ref | Contribution / Approach | Advantages / Findings | Limitation(s) |
|---|---|---|---|
| [7] | Adaptive Virtual-Impedance Droop control using only local measurements for islanded microgrids | Balanced reactive power sharing, reduced circulating currents, improved voltage regulation (validated in HIL) | Limited performance validation under unbalance, distortion, and noise sensitivity |
| [8] | Microgrid Operation Control with Adaptable Droop Gains using robust min–max MPC | Improved renewable utilization, reduced conventional source reliance | Simulation-based; lacks large-scale real-time validation |
| [9] | Cascaded I-P–PDN controller tuned by Black-winged Kite Algorithm for Load Frequency Control | Reduced frequency deviation, overshoot, improved integration of EVs/BESS | Simulation-heavy; ignores communication delays and device limits |
| [10] | MPC framework for grid resilience and variable resource management | Explicit constraint handling, improved islanding/cold-start transitions | Computational burden, solver speed, and comms bottlenecks |
| [11] | ILC-based Adaptive Bidirectional Droop for hybrid AC–DC microgrids | Prioritized AC/DC regulation, improved dynamic IL converter response | Validated in MATLAB/Simulink only; no HIL or field results |

| | | | |
|---|---|---|---|
| [12] | Harmonic mitigation scheme for DC–AC microgrids with parallel VSIs | Reduced THD, better dynamic inverter cluster behavior | Simulations and small lab tests only; scalability unproven |
| . [13] | Hybrid AI + semiconductor device method for PQ mitigation | Adaptive to sags, swells, harmonics; reduced PQ events | No HIL or field demonstration; dataset representativeness unclear |
| [14] | Optimized SAPF with Golden Jackal Optimizer + anti-windup PI | Enhanced harmonic mitigation, THD reduction, stability | Offline tuning only; sensitive to parameter drift/noise |
| [15] | Optimal UPQC placement in distribution networks | Improved PQ indices with fewer devices | Exhaustive search too heavy for large grids; model accuracy assumed |
| [16] | Survey on harmonic mitigation in high-RES networks | Identified trade-offs among filters, converters, control methods | Mostly analytical; lacks extensive experimental validation |
| [17] | Integrated active-filter scheme for nonlinear load compensation | Improved THD, voltage profile, disturbance rejection | Limited testing under weak-grid and extreme transients |
| . [18] | ANN-based MPPT with multilevel inverter for EV charging PQ improvement | Enhanced energy optimization and harmonic suppression | Simplified EV fleet modelling; lacks field-scale trials |
| [19] | Bidirectional storage converter integrated with UPQC (DSP-based) | Mitigated sags, swells, harmonics while supporting storage | Long-term reliability under heavy cycling not tested |
| [20] | Grid-Forming Active Power Filter (GFMC APF) for weak grids | Combined V/f regulation with harmonic mitigation | Multi-unit GFMC stability under imbalance not studied |
| [21] | GRU-based neural UPQC compensator | Faster disturbance tracking vs classical schemes | Generalization to unseen faults uncertain; retraining needed |
| [22] | Model-free predictive direct control for UPQC (FCS-MPC variant) | Robust to mismatch, fast transient compensation | Requires high computation and fast switching hardware |
| [23] | Hybrid storage + control for PV-based EV charging stations | Reduced THD, stabilized voltage during charging demand | Lacks feeder-level aggregated impact analysis |
| [24] | ANN-based Solar-PV UPQC with adaptive LMS | Improved PQ under sags/swells/THD | Training data dependency; atypical fault robustness untested |
| [25] | Review of PQ improvement methods (ML-enabled, hybrid APF/UPQC) | Summarized state-of-art, identified open gaps | No experimental validation; conceptual only |

## IV. LOAD SHARING AND BALANCING

A comparative review of power-sharing control topologies highlighted droop, virtual-impedance, and hierarchical methods for parallel inverters, noting better accuracy but still no experiments in weak grid environments [27]. A Luenberger-observer-based approach advanced power-sharing in islanded DC microgrids by estimating PCC deviation, which improved voltage balancing, but the need for exact models and measurements reduced its robustness [28]. Adaptive virtual complex-impedance control was proposed to eliminate sharing errors induced by complex impedance and automatically tune resistance and inductance, which reduced circulating currents. Its fast dynamics sensitivity became a challenge [29]. Integrated Primary and Secondary layers for Nanosatellite DC Microgrid Secondary Controllers achieve a hierarchical control scheme that achieves constrai ned accuracy power sharing. Its adaptation to systems outside space is still not but tested [30]. Active/reactive power sharing, with device constraints and uncertainties, was optimized in real time using a distributed controller. Still, the restrictions concerning the quality of communication and synchronization procedures are an unresolved drawback [31].Discrete-time accumulative control was proposed to address voltage regulation and active power sharing for grid-forming microgrids. Unfortunately, the concept has no known implementations to support it [32]. Feeder dependency was reduced in a two-layer microgrid community energy-sharing framework that combined economic feeder-based allocation and fast local power sharing. However, the dated solutions for mixed assets and user behavior continue to pose problems [33]. An improved framework for advanced load-frequency regulation was established to mitigate frequency deviations by coordinated support from PV, wind and EVs, as well as the sharing of regulation burden. It is still dependent on the robust dispatch, communication and EVs management systems for effective implementation [34].Temporary load redistribution and control saturation handling were suggested to avoid inverter overload in large transient systems while improving survivability. System complexity is increased and long-term device stress is also increased due to supervisory logic, which is an added overhead [35]. The self-coordinated sliding mode control scheme enhanced active power sharing and voltage regulation as the load changed. Nonetheless, practical implementations are limited because of the risks for chattering, switching losses, and the scant experimental validations [36].

## V. CONTROL TECHNIQUES FOR RENEWABLE SOURCES

The adaptive perturbe-and-observe technique and finite-control-set model-predictive control (FCS-MPC) used in hybrid MPPT improved the power quality and dynamic tracking of PV inverters. However, the real-time hardware performance and robustness under partial shading remain unexplored. [37]. Although the irradiance and temperature changes have been handled using LSTM and fuzzy logic, the inference overhead on a constrained processor and the lack of complete training data sets has made more comprehensive approaches infeasible. [38]. The shading dynamics were managed with global MPPT using Gaussian process regression combined with sliding-mode control, which was later proven to require a lesser generalizability to new PV arrays and lesser computational cost. [39]. Using grid-forming MPC, a low-voltage grid supported motion and frequency were enhanced using a single-stage PV inverter, but the slow solvers and the high cost of implementations in larger networks made adoption impossible. [40]. PC-grid-forming inverters that are synchronous-machine emulators have further improved the interoperability of PV, storage, and older machines. Still, their large-scale grid and stability margin effects have not been properly evaluated. [41] With an NPID droop variant, grid-forming microinverters further improved the PV dynamics and islanding behavior, but their behavior under highly unbalanced conditions has to be evaluated with more experimental conditions. [42] The weighted heuristic MPPT enhanced convergence speed and boost-converter stability, but evaluations on different converter topologies and with larger systems have not been conducted [43]. While reviews of MPPT AI algorithms and wide-bandgap semiconductors exposed certain industry developments, they lacked experimental data, making them more surveys than empirical studies. [44]. The MPC deep observer along with the tower-top IMUs of the wind turbines provided enhanced load alleviation and dynamic response; however, their complexity and sensor-failure resilience posed further problems. [45]. The robust MPC for wind turbine control was successfully tested on a testbed and, in addition, verified for pitch-model uncertainties; however, the tuning for a specific platform impairs its use on other types of turbines. [46]. an adaptive economic nonlinear MPC attempted to optimize turbine lifetime and production by trading off fatigue and revenue. However, this proved commercially infeasible due to the reliance on accurate price and fatigue models. [47]

**Table 3: Control Techniques for Renewable Sources**

| Ref | Contribution / Approach | Limitation(s) |
|---|---|---|
| . [37] | Hybrid MPPT combining FCS-MPC with adaptive P&O for PV inverters; improves dynamic MPPT and PQ | Mostly simulation; hardware timing/compute limits and shading robustness need HIL/field validation |
| [38] | LSTM + fuzzy logic dynamic MPPT for PV under variable irradiance/temp | Dependent on training data; inference overhead on constrained DSPs not resolved |
| [39] | Global MPPT using GPR + sliding mode control for shading/fast irradiance | GPR compute cost; generalization to unseen PV arrays uncertain |
| [40] | MPC-based grid-forming single-stage PV inverter; predictive V/f support | Requires fast solvers and precise models; impractical for low-cost inverters |
| [41] | Hybrid-Compatible Grid-Forming Inverters (HC-GFIs) for PV + storage + legacy machines | Large-scale stability impacts under multiple HC-GFIs not yet tested |
| [42] | Grid-forming microinverter with NPID droop variant for PV dynamics/islanding | Sensitive tuning; weak/unbalanced conditions not fully validated |
| [43] | Weighted-strategy MPPT for boost converters under fluctuating irradiance | Only small test cases; converter topology robustness unclear |
| [44] | Overview of MPPT trends: AI, wide-bandgap, advanced controllers | Industry-level summary; lacks original experiments |
| . [45] | MPC for wind turbines using tower-top IMU observer to improve dynamics/load alleviation | MPC complexity; robustness to sensor faults not shown |
| [46] | Robust MPC for wind turbine control (practical testbed study) | Controller tuning may not generalize to other turbines |
| [47] | Adaptive economic NMPC for turbines balancing revenue vs fatigue | Relies on accurate price/fatigue models; no commercial deployment yet |

## VI. CONCLUSION AND FUTURE WORK

This paper analyzed the latest developments in the control of AC microgrids integrated with HRES to understand the control requirements of modern renewable systems better. Conventional distributed control methods built around the droop and virtual-impedance control schemes are unable to meet the stringent requirements of modern control. The newer methods, for example, MPC, AI-based control, and adaptive control methods, provide better control performance in terms of voltage regulation, frequency control, power sharing, and harmonic mitigation. Even though the integration of renewables with energy storage improves dependability and sustainability, issues such as cyber-attacks, storage scalability, synchronization errors, and excessive computation still persist. All the works analyzed show the same pattern: research is primarily conducted through simulations, whereas large-scale and pilot project implementations and their evaluations remain scarce. While distributed MPC and AI controllers for micro controllers seem the most promising in terms of flexibility, adaptability, and dependability, the need of fast communication and computational infrastructure greatly limits their adoption. In addition, although newer load-sharing methods show marked improvement in the distribution of load between heterogeneous inverters, performance under weak grid conditions and widely different inverter parameters still remains suboptimal. In future research, integrating predictive models with microgrid controls and resilient communication infrastructures will be necessary to enable the development of robust, scalable, and adaptive control frameworks.

**REFERENCES**


[1] S. Adiche, M. Larbi, D. Toumi, R. Bouddou, M. Bajaj, N. Bouchikhi, A. Belabbes, and I. Zaitsev, “Advanced control strategy for AC microgrids: a hybrid ANN-based adaptive PI controller with droop control and virtual impedance technique,” *Scientific Reports,* vol. 14, art. no. 31057, 2024.

[2] Q. Wang et al., “Adaptive control strategy for microgrid inverters based on Narendra model,” *Scientific Reports*, 2024.

[3] S. Harasis et al., “Controllable Transient Power Sharing of Inverter-Based Distributed Generators in Microgrids,” 2024.

[4] K. N. Y. Saimadhuri, “A review of droop control and virtual impedance techniques,” 2024.

[5] F. Carnielutti, “Fixed Switching Frequency Model Predictive Control for Master-Slave Inverters in Microgrids,” *Revista de Energía Eléctrica (REP)*, 2024.

[6] L. S. N. Dangeti, “Distributed model predictive control strategy for microgrid frequency regulation,” 2025.

[7] H. Yang, Z. Sun, H. Wang, Y. Wang, M. Zhu, L. Guo, G. Zhou, and H. Lyu, “Adaptive Virtual Impedance Droop Control of Parallel Inverters for Islanded Microgrids,” *Sensors*, vol. 25, no. 16, art. no. 5166, 2025. MDPI

[8] E. D. Gomez Anccas, C. A. Hans, and D. Schulz, “Microgrid Operation Control with Adaptable Droop Gains,” arXiv:2506.15192, Jun. 2025. arXiv

[9] I. Khan, S. A. Malik, A. Daraz, B. Bareer, et al., “Enhanced load frequency regulation in microgrids with renewable energy sources and electric vehicles,” *Scientific Reports*, vol. 15, art. no. 26634, 2025. Nature

[10] J. Young, D. G. Wilson, W. Weaver, and R. D. Robinett, “A Model Predictive Control to Improve Grid Resilience,” *Energies*, vol. 18, no. 7, art. no. 1865, 2025. MDPI

[11] C. Ding, R. Zhao, H. Zhang, and W. Chen, “Research on Adaptive Bidirectional Droop Control Strategy for Hybrid AC-DC Microgrid in Islanding Mode,” *Applied Sciences*, vol. 15, no. 15, art. no. 8248, 2025. MDPI

[12] B. Sahoo, S. R. Samantaray, and M. M. Alhaider, “Advanced control scheme for harmonic mitigation and performance improvement in DC–AC microgrid with parallel voltage source inverter,” *Scientific Reports*, vol. 15, art. no. 7051, 2025. Nature

[13] R. Chinthaginjala, et al., “Hybrid AI and semiconductor approaches for power quality enhancement: a data-driven framework,” *Scientific Reports*, 2025. Nature

[14] D. Bakria, et al., “An optimized Shunt Active Power Filter using the Golden Jackal Optimizer for harmonic mitigation,” *Scientific Reports*, 2025. Nature

[15] J. S. Espinosa Gutiérrez and A. Aguila Téllez, “Optimal Placement of a Unified Power Quality Conditioner (UPQC) in Distribution Systems Using Exhaustive Search to Improve Voltage Profiles and Harmonic Distortion,” *Energies*, vol. 18, no. 17, art. no. 4499, 2025. MDPI

[16] Z. Reguieg, I. Bouyakoub and F. Mehedi, “Harmonic mitigation in grid-integrated renewable energy systems with nonlinear loads,” *Energy*, vol. 324, 2025. ScienceDirect

[17] R. Boopathi, et al., “Enhancement of power quality in grid-connected systems using active power filter integration,” *Scientific Reports*, 2025. Nature

[18] G. Vijaykumar, et al., “Integrated energy management and harmonic mitigation in a microgrid using sea-gull ANN MPPT and advanced multi-level inverter,” *Ain Shams Engineering Journal*, vol. (article no.), 2025. ScienceDirect

[19] T. H. Wu, et al., “Application of bidirectional energy storage converter in UPQC-integrated distribution systems,” *Electrical Power and Energy Systems*, 2025. ScienceDirect

[20] M. W. Qaisar, et al., “Modeling and Control of Grid-Forming Active Power Filters for harmonic control and voltage/frequency regulation,” *Applied Sciences*, vol. 15, no. 11, 2025. MDPI

[21] B. S. Goud, et al., “GRU controller-based UPQC compensator design for power quality enhancement,” *(Journal/Conference)*, 2025. PubMed

[22] G. Wang, et al., “Model-Free Predictive Direct Control of Unified Power Quality Conditioner (UPQC),” *IET*, 2025. IET Research

[23] A. Manjula, et al., “Power quality improvement of microgrid for photovoltaic EV charging stations with hybrid energy storage system,” *ScienceDirect / Elsevier* (article), 2025. ScienceDirect

[24] C. L. Babu, et al., “An Artificial Neural Network Control Based Unified Power Quality Conditioner (UPQC) for PV systems,” *NJSTR / region journal*, 2025. journals.nipes.org

[25] P. R. Kumar, “A Review of Emerging Techniques for Power Quality in High-RES Systems,” *E3S Web Conferences / ICREG CSD 2025 proceedings*, 2025. E3S Conferences

[26] G. Ramasamy, “Advanced Compensation-Based Power Quality Solutions for Smart Microgrids,” *Energy Technology / EnTE (Wiley)*, 2025. Wiley Online Library
[27] M. H. Khan, S. A. Zulkifli, N. Tutkun, and M. Şimşir, “Progressing Towards Sustainability: Power-Sharing Control Topologies for Microgrids with Parallel-Connected Inverters for Grid Stability,” *Sustainability*, vol. 17, no. 10, art. no. 4277, May 2025. MDPI
[28] M. Tesfaye, “Enhanced Power Sharing Control of an Islanded DC Microgrid Considering Line Impedance and Load Variation,” *Electronics*, vol. 14, no. 8, art. no. 1654, 2025. MDPI
[29] J. Ma, “Adaptive Virtual Complex Impedance-Based Power Sharing Control for Parallel Inverters,” *IET Smart Grid*, 2025. IET Research
[30] K. Louassaa, J. M. Guerrero, B. Khan, M. Z. Yousaf, M. A. Zdiri, L. Zhang, R. Sivanraju, et al., “Enhanced power sharing and voltage regulation for islanded nano-satellite DC microgrids in spinning flight scenarios,” *Scientific Reports*, vol. 15, art. no. 30415, 2025. Nature
[31] A. Khan, “A real-time distributed optimization control for power coordination in inverter-based microgrids,” *Journal / Conference (ScienceDirect)*, 2025. ScienceDirect
[32] M. P. Contzen, “Power sharing and voltage regulation control for grid-forming inverter networks: a discrete-time accumulative control strategy,” *Electric Power Systems Research* (ScienceDirect), 2025. ScienceDirect
[33] J. Wu, “An energy sharing framework for improving load supply and renewable utilization in community microgrids,” *Renewable Energy*, 2025. ScienceDirect
[34] I. Khan, S. A. Malik, A. Daraz, B. Bareer, et al., “Enhanced load frequency regulation in microgrids with renewable energy sources and electric vehicles,” *Scientific Reports*, vol. 15, art. no. 26634, 2025. Nature
[35] J. Westman, “Overload mitigation for grid-forming inverters in islanded microgrids,” *Electric Power Systems Research*, 2025. ScienceDirect
[36] W. Zhang, “A voltage-power self-coordinated control system on the microgrid using sliding-mode control,” *ScienceDirect / Journal*, 2025. ScienceDirect
[37] B. Naima, et al., “Enhancing MPPT optimization with hybrid predictive and adaptive P&O for photovoltaic inverters,” *Scientific Reports*, 2025. Nature
[38] M. A. Fkirin, “Dynamic Controller Design for Maximum Power Point Tracking using LSTM and Fuzzy Logic,” *Technologies*, vol. 13, no. 2, art. 71, 2025. MDPI
[39] M. T. Kaaitan, “A novel global MPPT method based on sooty tern (GPR + HOSMC),” *Scientific Reports*, 2025. Nature
[40] X. Zeng, “Predictive Control for Grid-Forming Single-Stage PV Inverters in Low Voltage Grids,” *Sustainability*, vol. 17, no. 11, 2025. MDPI
[41] B. Bhowmik, “Hybrid-Compatible Grid-Forming Inverters (HC-GFIs): system realization and control,” *Scientific Reports*, 2025. Nature
[42] M. A. Syahbani, “Performance enhancement of grid-forming inverter for PV integration using NPID droop control,” *Energy Conversion and Management / Applied Electronics*, 2025. ScienceDirect
[43] L. El Oussoul, “A new MPPT control strategy based on a weighting mechanism for boost converters,” *Electric Power Systems / Renewable Systems*, 2025. ScienceDirect
[44] RLD Power industry summary, “MPPT Controller for Solar PV Systems in 2025,” rldpower.com, Apr. 27, 2025. rldpower.com
[45] Y. Wang, S. Zhu, R. Deng, et al., “Model predictive control of wind turbine based on deep-dive holistic observer of tower top IMU,” *Applied Energy*, vol. 392, 2025. ScienceDirect
[46] A. Klein, T. Wintermeyer-Kallen, J. Zierath, et al., “Design and Practical Evaluation of Robust Model Predictive Wind Turbine Control,” *Wind Energy*, 2025. TU Delft Research Portal
[47] A. Anand, “Adaptive economic nonlinear MPC for wind turbines with fatigue-aware cost,” *Wind Energy Systems / WES preprint*, 2025. WES