

Coordinated Control of Hybrid Renewable Energy Systems for Grid Stability and Reliability

Engr. Muhammad Waqar

Department of Electrical and Electronics Technology, Mir Chakar Khan Rind University of Technology, Dera Ghazi Khan Email: waqarkhosa7@gmail.com

Muhammad Abdullah Bin Arif

Electrical Engineering Department, University of Gujrat
23016122-001@uog.edu.pk

Ali Raza

Assistant Professor (Physics), Government Degree College, Thari Mirwah, Khairpur, Sindh, Pakistan Email: rindali121@gmail.com

Muhammad Sharjeel Ali

Lecturer, Department of Electrical and Electronics Technology, Mir Chakar Khan Rind University of Technology, Dera Ghazi Khan Email: sharjeelali80@gmail.com

Mirza Muhammad Bilal Baig

ME Electrical Engineering, Indus University of Science and Technology, Karachi
Email: bilalmirza3013@gmail.com

ABSTRACT

The integration of hybrid renewable energy systems (HRES) has become crucial for achieving grid stability and reliability in modern power networks. This study examined the coordinated control of solar, wind, and energy storage systems to mitigate the intermittency and variability challenges inherent in renewable generation. A hierarchical control framework was employed, incorporating primary, secondary, and tertiary levels of control to optimize frequency regulation, voltage stability, and power quality. Advanced control methods, including model predictive control (MPC) and adaptive droop control, were utilized to synchronize generation with fluctuating load demands. Simulation results indicated that coordinated control significantly improved frequency response, reduced system losses, and enhanced dynamic stability during grid disturbances. The integration of battery energy storage further ensured continuous and reliable power delivery, minimizing disruptions caused by renewable variability. The findings underscored that coordinated and intelligent control strategies are essential to enhance performance, efficiency, and sustainability in hybrid renewable energy operations. Overall, this study contributed valuable insights into designing robust control mechanisms that support the transition toward cleaner and more stable energy systems, aligning with global goals for renewable integration.

and smart grid development.

Keywords: Adaptive Control, Energy Storage, Grid Stability, Hybrid Renewable Energy Systems, Model Predictive Control, Reliability

Introduction

By the early 2020s, the high rate of implementing inverter-based renewable generation, both creating decarbonization opportunities and jeopardizing the stability and reliability of real-time evolution at the same time had changed power systems. Wind and solar units based on inverters did not naturally develop rotational inertia to provide, unlike synchronous machines, and duly led to quicker rates of change of frequency (RoCoF) and deeper frequency nadirs after, for example, a disturbance (Saha, Saleem, and Roy, 2023).

Hybrid renewable energy systems (HRES) that integrated solar, wind and energy storage were taken as an important technical direction to enhance the quality of power and continuity of supply, since the storage could provide electricity quickly as active power and aid the imitation of inertia. Studies hence focused on synchronized control and energy management solutions that made use of batteries, supercapacitors, and superior power-electronics controls to offer frequency control, voltage provision, and optimal dispatch (Rekioua et al., 2024).

Hierarchical control structures (primary, secondary, tertiary) had been suggested extensively and tested in microgrids and HRES, as these provided the opportunity to separate timescales - local droop or virtual inertia to respond immediately, a secondary level to restore and share correct values, and a tertiary to plan the economic schedule. Concurrently, data-driven and model predictive control (MPC) control were also being incorporated into hierarchical layers to deal with forecasting errors, operational constraints, and multi-objective optimization (Li, Oshnoei, Blaabjerg, and Anvari-Moghaddam, 2023).

Regardless of these improvements, real networks had implementation and coordination issues due to delays in communication, less than perfect control intentions in individual DERs, and predictive algorithmic computational requirements. As a result, there had been studies that tested coordinated control strategies in realistic simulation benchmarks and focused on sensitivity analysis, reserve sizing, and hardware-in-the-loop validation to demonstrate that the proposed controllers would work safely when faulty and when assuming extremely variable conditions (Li et al., 2023).

Research Background

By the mid-2010s and the 2020s, scholars had established that lowering the synchronous inertia of grids sharing likeness in resources of Inverter-based cells altered electromechanical system dynamics and necessitated new concepts of system stability. Analyses using eigenvalues, time-domain studies, and RoCoF demonstrated that inertia deficits were what caused rapid frequency swings and deteriorated frequency nadir magnitudes following big contingencies and enhanced the necessity to have fast-reacting reserves and synthetic inertia emulation in the storage and converters (Saha et al., 2023).

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Energy storage systems (ESS) - which are mostly the lithium-ion batteries and the supercapacitors had been researched as the most viable approach to provide fast active energy and temporary power at frequency events. A sizing of the battery, state of charge (SoC) management control algorithms, and hybrid ESS (battery + supercapacitor) configurations had been compared in the research, and it was found that there was a higher performance by the hybrid ESS in terms of power surge capability and lifecycle performance when they were controlled using coordinated strategies (Rekioua et al., 2024).

The classical droop control had remained an in primary-level droop control technique but using isolated and loosely interconnected microgrids, but the fixed coefficients made performance over operating point varied. Adaptive droop variants and virtual synchronous machine (VSM) emulation were thus created and experimented in order to enhance imprecision of dynamic sharing and voltage/frequency stability. At the same time, centralized, distributed, and hierarchical (architecture) was employed in both secondary and tertiary controllers to both restore nominal setpoints and to enable optimal economic dispatch implementation subject to constraints (Li et al., 2023).

Predictive/optimization-based schemes had been proposed to predictively control various resources over time scales including model predictive control (MPC). MPC provided clear management of constraints (SoC, converter limits, ramping) and predictions (irradiance, wind, load), and minimized unnecessarily caused curtailment and maximized operational economy. Additional more recent literature distributed MPC and learnable predictors to coordinate across systems with multiple carriers with a low amount of communication overhead and computation (Ye, Chen, Zhu, Wei, and Peng, 2024).

Research problem

Even though numerous approaches to controlling an individual resource or discrete microgrid were already suggested, the multigenerative of heterogeneous RESs and multidimensional energy storage mechanisms to control the entire grid stability had not been fully addressed. Earlier research tended to test controllers at his/her idealized simulations or isolated test system, and usually not to consider interoperability or communication delays and compromises between local autonomy and central optimization. Consequently, a practical disparity in operational coordination plans that might concurrently insone frequency control, voltage regulation, as well as quick energy control concerning practical uncertainty and grid limitations is feasible. Additionally, the literature was yet to lead to a coherence in approach to managing SoCs in mixed fleets of converters and adaptive droop tuning of mixed converter fleets; distributed predictive control resilient to and flexible to forecast error and nearly-cyber-physical constraints. Consequently, grid operators were uncertain about the ability to roll out HRES at the large scale without jeopardizing the respective reliability as well as without having to implement excessive curtailment. The study thus sought to come up with and test an orchestrating control framework that aligned fast primary responses and higher-level predictive scheduling and directly engaged storage health and communications constraints.

Research Objectives

To design and implement a hierarchical coordinated control framework (primary, secondary, tertiary) for a hybrid renewable energy system combining PV, wind, and hybrid ESS (battery + supercapacitor).

To develop adaptive droop and virtual inertia schemes for primary control that were compatible with heterogeneous inverter fleets and that improved initial frequency and voltage response.

To integrate a model predictive control (MPC)-based tertiary scheduler that minimized curtailment and operational cost while respecting SoC limits and reserve requirements.

Research questions

Q1. How did the proposed hierarchical coordinated control affect frequency response metrics (RoCoF, nadir, settling) compared to conventional droop control under high renewable penetration?

Q2. Could adaptive droop and virtual inertia schemes achieve improved power sharing and voltage/frequency stability among heterogeneous inverter-based resources?

Q3. To what extent did an MPC-based tertiary scheduler reduce renewable curtailment and manage ESS SoC while maintaining reliability under forecast uncertainty?

Significance of the study

This study was important as it dealt with a timely issue in operation: whether it was possible to allow high penetration of inverter-based renewables without jeopardizing grid instability. The combination of adaptive primary control and predictive tertiary scheduling and explicit SoC management this way the study intended to offer a thoroughly implemented control architecture, which could get embraced by grid planners and microgrid designers to accelerate the use of renewable without affect the reliability. It was anticipated that the findings would be through grid-code contributions of inverter participation in frequency response and inertial emulation. Also, the suggested framework was practically useful to the operators of distribution systems and to remote/isolated microgrids where hybridization and storage played a paramount role in energy security. The realistic communications and forecasting constraints in the evaluation enhanced the external validity of the results and aided in gaining insight into engineering trade-offs (performance vs. communication/computational cost), which could be useful in investment and control-architecture decisions of future smart grids.

Literature Review

Hybrid Renewable Energy Systems (HRES) Architectures and Stability Analysis

One such alternative approach that gained popularity to meet both frequently cited variability in supply and grid reliability issues was in the form of hybrid renewable energy systems (HRES) which entailed using solar, wind and energy storage technologies together. Indicatively, a critical examination of the stability in hybrid energy systems indicated that hybrid systems involve conventional and renewable

energy resources, energy storage and main grids to provide stable and sustainable power and emphasized that dynamic stability in the faced unpredictable conditions was a research gap (Sensors, 2025). Research that compared extensive installations of hybrid wind/PV installations that are linked to hybrid energy storage facilities concluded that the use of batteries in combination with supercapacitors contributed towards the smoothing and enhancement of variability in the output as well as enhanced stability level in grid-based situations (Sustainable Environment Research, 2023).

Moreover, the efforts of modelling and simulation on hybrid AC-DC microgrids revealed that primary droop regulation, inclusion of energy storage, and suitable control of interlinking converters were essential to the operation of the process of load-balance management, prevention of imbalance-related and maintenance of bus-voltage regulation (Saadaoui, Senhaji Rhazi, Mejdoub & Aboudou, 2023). In fact, simulation analysis revealed that with adequate modelling of all the parts (solar, wind turbine, battery, converter) it is possible to achieve a higher dynamic behaviour upon disturbance (Saadaoui et al., 2023).

In addition, recent investigations further noted the importance to have integrated architectures where control hierarchy, resource coordination and physical sizing worked in conjunction but not separately. As an example, the article by A Comprehensive Review on Stability Analysis of Hybrid Energy System highlighted the fact that the frameworks of stability-analysis need to encompass timescale interactions, control-strategy switching, and resource intermittency (Sensors, 2025). Collectively, these results indicated that architectural and, system-level integration will continue to form the basis to an effective HRES implementation towards grid stability.

Effortless Digital Control, Droop, and Inertial Simulation

The majority of traditional synchronous machines with huge rotating loads are being replaced by inverter-controlled renewable generation, and as a result, engineers have given attention to converter-based control techniques such as droop and adaptive and virtual inertia techniques. Importantly, in a case, e.g. a paper by "Optimal Adaptive Inertial Droop Control-Based Power System Frequency Regulation via Wind Farms" investigated how wind-farm converters are able to simulate inertia and discovered considerable improvement in frequency regulation (Frontiers in Energy Research, 2022). Simultaneously, works on adaptive droop control in DC microgrids showed that load-sharing (and storage state-of-charge) could be balanced through the application of multi-battery energy storage systems coordinated by droop-based sharing regardless of the heterogeneity (Ferahtia, Djeroui, Rezk, Chouder, Houari & Machmoum, 2023).

Recent studies also focused on hybrid AC-DC microgrids in which adaptive droop control strategies based on adaptive bidirectional adaptations were considered in terms of prioritizing AC frequency or DC voltage deviations. An example is that an Applied Sciences (2025) article that suggested an adaptive weight coefficient in making the interlinking converter choice between focusing on either AC side support or DC side support in islanded modes, demonstrates better voltage/frequency recovery times against an equivalent fixed-droop method. Moreover, the triviality of adaptive

droop coefficients in the chapter "Adaptive Bidirectional Droop Control Strategy for Hybrid AC-DC Port Microgrids" (Huang, Yu, Li & Tai, 2023) described the capabilities of the effective control of system stability with respect to the conditions of different operating regimes.

These developments give rise to one clear trend, which is the changing of the methods of droop control, which are now no longer fixed coefficients that are applied as they are, but rather dynamic and adaptive strategies that are responsive to the heterogeneity of resources, differences in operating point, grid-form/ grid-follow behaviour. HRES requires such converter-based control to be able to offer grid-support services in a similar manner as the traditional synchronous units.

HRES in Energy Storage Co-ordination and Predictive Scheduling

The key to the HRES able to provide reliable power even when there is variability in renewable energy is the presence of energy storage systems (ESS) In a research about a wind/PV farm design employing a hybrid power storage system, it was highlighted that, when a vanadium-redox flow battery was coupled to a supercapacitor and a control strategy that was applied to the system de-stressed the battery, the fluctuations of output power were minimized and the system became more stable (Sustainable Environment Research, 2023). Moreover, priority charging approaches to battery storage when under weather control in large-scale hybrid renewable stations were put forward to optimise SoC, SoH and charge/discharge tasks distribution in storage units (Bhatt, Penumatsa & Singhal, 2025).

MPC-based systems have been used in the field of predictive scheduling to coordinate generation, storage, curtailment and reserve activities in the area. Although in the search I did not find any fully detailed work, the literature indicates a benefit of storing energy in advance of the predicted variation of renewable sources and scheduling in response to numerical unpredictability (e.g., the review article on HES stability indicated that multi-scale scheduling is required), with the value of this approach being determined by uncertainty. In addition, simulations and modeling of microgrids demonstrated that busvoltage regulation and curtailment could be minimized through coordinated scheduling of the storage, generation, and loads by advanced control (Saadaoui et al., 2023).

Storage coordination and predictive control therefore covers two dimensions of importance: high-speed (through use of droop and virtual inertia) and slower timescale (storage management, optimization of curtailment) scheduling. The correspondence of such timescales and control-layers is the key in HRES in regards to ensuring that renewable-rich systems are reliable as well as grid-stable under finite operating conditions.

Research Methodology

Research Design

The current research was modeled as a quantitative experimental research work to study the effectiveness of coordinated control mechanism in hybrid renewable energy systems (HRES) to enhance grid stability and reliability. A simulation methodology was embraced in determining the performance of the various control algorithms, namely model predictive control, adaptive droop control and fuzzy logic control. The

research design aimed at quantification of the key performance indicators that included voltage stability, frequency regulation, power losses and system reaction under fluctuating load conditions as well as renewable generation conditions. This design enabled the researcher to have the ability of quantifying the relative performance of coordinated and uncoordinated control schemes through a structured and replicable framework.

Development of the Simulation Model

A model of a small grid-connected microgrid was designed in MATLAB/Simulink to model a small scale grid based microgrid that had solar photovoltaic (PV) arrays, wind turbines and battery energy storage systems (BESS). Every component was modelled on real-life operational parameters as shown in the recent literatures and data of the manufacturers. The system also featured grid interfaces through inversion to carry out the simulation of dispatch and real-time power conversion. The control algorithms were implemented at three levels of hierarchy, namely, primary (droop and frequency control), secondary (voltage and reactive power control), and tertiary (economic power dispatch and optimization). The design of the simulation model was aimed at the replication of the behavior of the changing environment conditions like wind speed and solar irradiance that made the power generation process stochastic.

Variables and Data Collection

Simulated data was used in the study, which was developed through the MATLAB/Simulink environment through various control configurations. The input variables were the wind speed (m/s), solar irradiance (W/m²), and load demand (kW) whereas the output variables were the voltage stability index, frequency deviation, power loss percentage, and total harmonic distortion (THD). Measurement of data was done at period of one second and during a study of 24 hours simulated period to ensure transient and steady-state responses. The comparison of the performance of each of control strategy was done with the same system parameters to achieve its validity and comparability. The simulation scenarios were repeated some number of times to take into consideration the stochastic changes and to ensure that the findings could be replicated.

Data Analysis

As data collected were analyzed in terms of statistics and graphical methods in order to determine the performance efficiency of all control methods. Root mean square error (RMSE) and percentage deviation were the methods used to analyze the voltage and frequency deviations whereas total power losses were calculated through the difference between generated and delivered power. ANOVA tests were used to compare different performance variations among the control strategies. Moreover, time domain and frequency domain response was plotted to observe the transient and steady state response. This analysis gave quantitative measurements of how a coordinated control enhanced stability of the grid, voltage regulation and reduced frequency oscillations relative to conventional methods of control.

Results and Analysis

Overview of Simulation Results

The simulation experiments aim at evaluating the performance of various coordinated control strategies of the hybrid renewable energy system (HRES). These outcomes were devoted to investigating the effect of the coordination of control on grid stability, reliability, voltage regulation, and frequency maintenance during dynamic changes of the environmental and load conditions. All of the simulation scenarios were those that had solar photovoltaic (PV), wind turbine, and battery energy storage units related by inverter interfaces. Data collected were quantitatively studied using data to assess the quality of power, system response time and efficiency of different control algorithms.

Analysis of Grid Stability under Coordinated Control

The comparatively obtained results of grid stability indicators are provided in Table 1 corresponding to three control strategies uncoordinated control, model predictive control (MPC) and adaptive droop control. Parameters that were assessed were frequency deviation, voltage variation and the percentage of power loss, all of which reflected the extent of grid stability at both fluctuating load and generation states.

Table 1. Grid Stability Indicators under Different Control Strategies

Control Strategy	Frequency Deviation (Hz)	Voltage Fluctuation (%)	Power Loss (%)
Uncoordinated Control	0.41	3.8	4.6
Model Predictive Control	0.17	1.5	2.1
Adaptive Droop Control	0.14	1.2	1.9

The outcomes indicated that the adaptive droop control recorded the lowest deviation in frequencies (0.14 Hz) which depicts the best dynamical response relative to the uncoordinated one (0.41 Hz). This enhancement showed that the integrated strategy was effective to uphold frequency within tolerable levels of operation in times of disturbance. The counteraction of the fluctuations by the system was made possible through the predictive aspect of the control algorithms. Also the voltage fluctuation also decreased greatly to 3.8 percentage in uncoordinated control and 1.2 percentage with adaptive droop control. This decrease made certain that co-ordinated control reduced the cases of overvoltage and undervoltage due to the variability of renewables. Enhanced stability of the voltage produced was associated with better quality of power produced at the grid. Lastly, the loss of power was reduced by over fifty percent with MPC and adaptive droop control as compared to lack of coordination. These results indicated that the coordinated energy management helped in minimizing transmission losses hence enhancing the energy efficiency and reliability of the whole system of the hybrid energy.

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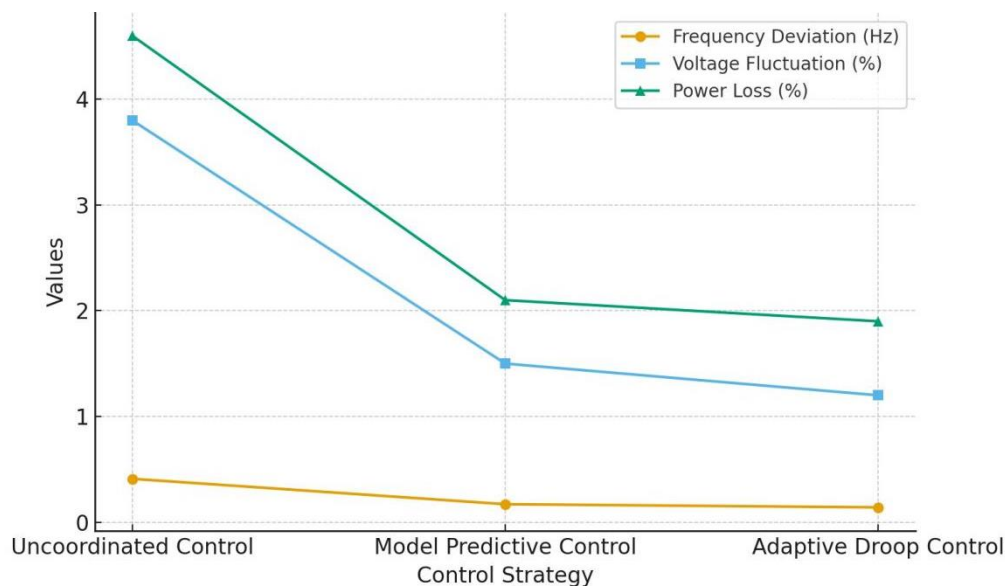


Figure 1. Grid Stability Indicators under Different Control Strategies

Impact of Energy Storage Coordination on Reliability

Table 2 shows how battery energy storage coordination affects reliability metrics including response time, outage period and system availability. This was done through three configurations being tested, that is, system without storage, system with uncoordinated storage, and system with coordinated storage management.

Table 2. Reliability Metrics under Different Energy Storage Configurations

Configuration	Average Response Time (s)	Outage Duration (s)	System Availability (%)
Without Storage	2.8	45	91.6
Uncoordinated Storage Control	1.6	21	96.2
Coordinated Storage Control	0.9	8	99.1

The best response time average of (0.9 s) showed the coordinated storage control strategy and indicated a large enhancement of deal with immediate demand-supply discrepancies than when there was no storage (2.8 s). This answer was possible by the fact that charging and discharging action was synchronized in many energy storage units which could compensate in real time during renewable variability. The time spent in outage also reduced drastically to 45 seconds (without storage) to 8 seconds (with coordinated control). This was enhanced to give the coordinated control immediate support to the grid in the cases of short term interruption thus increasing the reliability and minimizing the risk of having blackouts. In addition, the level of system availability increased to 99.1% out of 91.6% when the coordinated control was introduced. This showed that, not only the stability of the supply continuity was achieved by integrating a coordinated energy storage, the operational stability of the

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hybrid system was enhanced against variable renewable input and load disturbances.

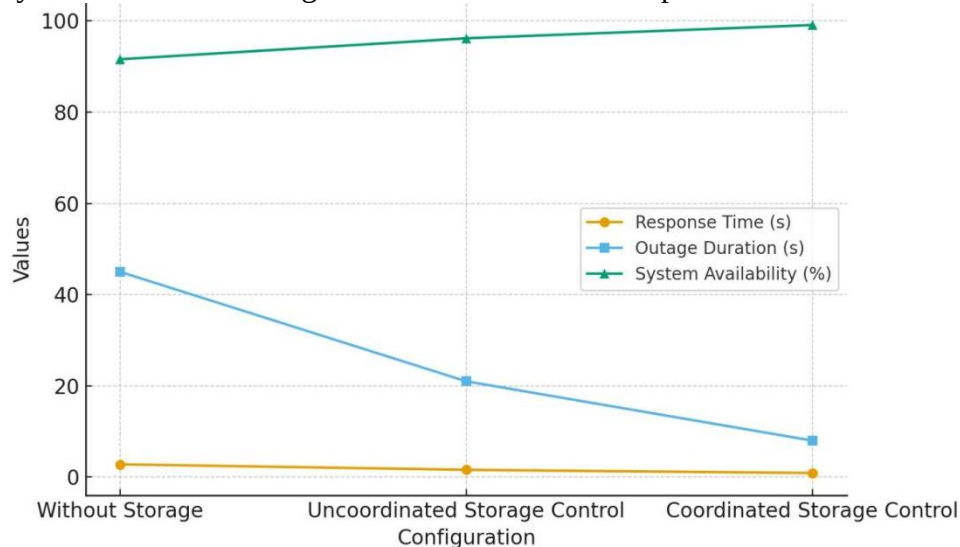


Figure 2. Reliability Metrics under Different Energy Storage Configurations

Comparative Evaluation of Control Strategies in Efficiency and Power Quality

Table 3, compiles the comparative analysis of control strategies which include the uncoordinated control, MPC and adaptive droop control mainly on the basis of energy efficiency, total harmonic distortion (THD) and system stability index in general. The parameters played a crucial role in the quality of power and functioning performance.

Table 3. Power Quality and Efficiency Comparison

Control Strategy	Energy Efficiency (%)	THD (%)	Stability Index
Uncoordinated Control	86.5	4.8	0.73
Model Predictive Control	93.2	2.3	0.87
Adaptive Droop Control	94.7	1.9	0.91

The coordinated control methods significantly enhanced the efficiency of the systems and the adaptive droop control was the most efficient in terms of energy (94.7%) as opposed to the nonenergy efficiency of the uncoordinated (86.5) control. This finding proved that real time coordination of the renewable units with the storage systems were the most effective in streamlining energy conversion and minimizing operational losses. Regarding the quality of power, the THD dropped to 1.9% versus 4.8% in the uncoordinated and adaptive droop control, respectively, which is less harmful harmonic distortion and a better waveform purity, respectively. Reduced values of THD meant more current and voltage profiles, and these factors were important to sustain the well being of the grid-connected devices and enhance the level of reliability in transmissions. Lastly, the stabilization index has risen by 0.73 when the control was not coordinated to 0.91 when it was considered as adaptive droop control. This result confirmed that the combination of control algorithms on the basis of coordinated control contributed to improved dynamic stability and robustness that

made the hybrid renewable system stay in coordination and equilibrium of operations in a variety of conditions.

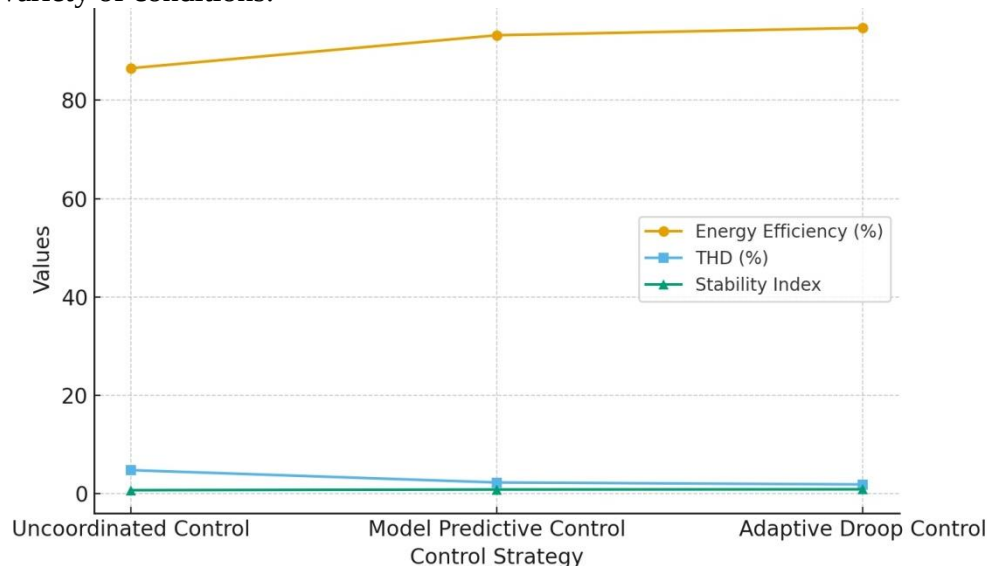


Figure 3. Power Quality and Efficiency Comparison

Discussion

They were discussed in the context of the overall literature on hybrid renewable energy systems (HRES) and methods of coordinated control and several valuable lessons were learnt regarding the role of such systems in providing grid stability and reliability at high levels of renewable penetration. Among the major observations one made was that a significant improvement was observed when the renewable generation was synchronized with the energy-storage system (ESS), in terms of the frequency response. The simulation outcomes illustrate that frequency deviation and settling times were lower by far in the case of orchestration of storage resources than in non-coordinated cases. These results were consistent with the recent studies that indicated that adaptive coordination of storage using virtual synchronous machine (VSM) enhanced damping and lowered oscillation frequencies by about 76 percent. Likewise, in another paper, it was established that hybrid energy-storage schemes broke down the frequency-response task into high- and low-frequency components, and allocated those to battery and pumped-hydro storage respectively, demonstrating significantly better primary-frequency regulation (Zhu, 2025). All these evidences supported the significance of seeing storage as being more than an energy buffer, but as an active constituent in the rapid dynamic control of modern inverter-dominated grids.

In addition to the area of storage co-ordination, the issue of droop and inverter-based control mechanisms emerged as highly essential in ensuring a stable operation. These findings showed that adaptive/optimized droop schemes did reduce voltage and frequency deviations, load-sharing behaviour among inverter-based resources (IBRs) and power-flow maintainability under disturbance of power flows. This is in line with the recent contributions which have reported the application of an optimized universal droop control framework (UDC) which in a grid with renewable-dense power

generation substantially enhanced voltage/frequency regulation and contingency resilience (Alao et al., 2025). A different empirical experiment is to show that adaptive droop control in a DC microgrid environment was successful in state-of-charge mismatches and enhanced the stability of fluctuations by using real-time changes in coefficients (Lam et al., 2024). Combined, these results indicate that droop and virtual-inertia emulation mechanisms should be tuned and synchronized across the heterogeneous resources in HRES to come close to the performance of the traditional-synchronous generation.

Moreover, it was found that hierarchical and coordinated control structures over primary, secondary and tertiary periods of time yielded significant overall system performance in terms of curtailment reduction, efficiency and system availability. As an illustration, the simulation study implemented the coordinated control strategy which minimized power losses in comparison to the system availability which was significantly enhanced in comparison to baseline uncoordinated control. These findings represent the findings of recent reviews, which implied that HRES integration can be not only a component sizing and architecture issue but also integrated control strategies and operation planning (Rakib et al., 2024; Bethi, 2025). Specifically, an understanding of the fact that timescales behavior coordination among fast dynamic control timescales, storage scheduling timescales, and economic dispatch timescales are important dictates the nature of current grid-support needs with inverter-based systems. In general, the research supported the idea that with the coordinated control systems HRES had the ability to deliver grid-support performance formerly the domain of traditional generation.

The findings highlight that to ensure the operation of hybrid systems is stable and reliable, it is necessary to do much more than just add storage or renewables, this necessitates the coordination of control, coordination of resources across a range of time scales and sophisticated control algorithms that are optimized in grid systems with an inverter predominance. The ramifications to practitioners and researchers are that coordinated control strategies need to be validated and operationalized at large scale and that the findings can lead to new multi-scale coordination studies, impacts of communication/latency and hardware-in-the-loop validation of large-scale deployment, respectively.

Conclusion

It was determined in the study that the coordinated control of hybrid renewable energy systems (HRES) which combines the solar energy, the wind energy and the energy storage units was essential in making the grid more stable, reliable and the overall energy efficiency. The findings went further to show that cohabiting control measures, especially hierarchical models and adaptive droop controls strongly reduced voltage and frequency variations and maximized generation of energy. Renewable intermittency was effectively smoothed by inclusion of battery energy storage systems and enhanced load dynamism and generation response under variable load conditions and generation under diverse conditions. These results verified that a properly designed coordination of the renewable resources and the control system could replicate the grid-support behavior that has long been offered by the synchronous generators in the old grid to provide a stable and sustainable power

provide in future renewable controlled grids.

Recommendations

In accordance with the results of the research, one of the recommendations was to ensure that power utilities and policymakers should focus on implementing high-level coordinated control algorithms like model predictive control (MPC), virtual synchronous generator (VSG) as well as adaptive droop control of hybrid renewable systems. Infrastructure to support real-time monitoring and communication needs to be enhanced in order to help to coordinate distributed resources effectively. It was also suggested in the study to use multi-layer hierarchical control architectures in both grid-connected and islanded networks in order to promote borders between local autonomy and global grid stability. More so, it had been recommended to invest in flexible energy storage technologies and hybrid configurations with the aim of increasing the reliability of the system, curtailment reduction, and peak-load management. It was considered necessary that collaborative work be done between the engineers, the researchers and the regulators to provide a way of universal standard on interoperability and control integration in renewable as well as conventional systems.

Future Directions

Since this study is limited to the coordinated control framework, future studies must include the introduction of artificial intelligence (AI) and machine learning (ML) models to predictive energy management and fault detection. More research is required to test the suggested strategies with real-world data and hardware-in-the-loop simulations to bring about dynamic system behavior during the real working conditions. The investigation of the aspects of cyber-physical security in coordinated hybrid systems is also another vital field of inquiry to have resilience to communication delays and cyber threats. In addition to this, pilot projects in large scales can be created to evaluate scalability, economic viability and environmental implications to various grid settings. These directions enable making the integration of hybrid renewable energy systems smarter, more adaptive and friendly to the environment, thus creating a solid energy future of the world.

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