

## Enhancing Grid Stability Through Wind Energy Integration Using Advanced Power Control Techniques



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### ABSTRACT

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Wind energy integration into power grids presents significant challenges due to its inherent variability and intermittency, which can adversely affect grid stability. This paper proposes a novel grid stabilization approach for wind energy systems based on intelligent power control techniques. The proposed method incorporates dynamic reactive power compensation and frequency regulation strategies to mitigate voltage and frequency fluctuations. The system is modelled and analyzed using MATLAB/Simulink, while real wind speed data obtained from the National Renewable Energy Laboratory (NREL) database are utilized to ensure realistic operating conditions. Furthermore, adaptive droop control and virtual inertia emulation are implemented to enhance system resilience against grid disturbances. Simulation results demonstrate that the proposed method improves voltage stability by maintaining the voltage level at approximately 0.96 p.u., reduces frequency deviations to within  $\pm 0.05$  Hz, and enhances overall grid reliability under dynamic wind conditions. In addition, the approach decreases reliance on conventional generation sources while maintaining stable grid performance. These findings highlight the effectiveness of advanced control strategies in facilitating the sustainable and reliable integration of wind energy into modern power systems.

## 1. INTRODUCTION

In the last twenty years, the world has undergone a revolution in renewable power, and, encouragingly, wind energy has emerged as one of the leading technologies for meeting the growing demand for clean, sustainable energy. Wind energy, through turbines, captures the kinetic energy of moving air and converts it into electricity; therefore, it is considered one of the most viable alternative energy sources [1]. Its relatively low cost, wide acceptance, and low carbon content make it one of the most widely used components of power systems worldwide [2]. Wind farms are widely deployed across vast areas, coastal regions, and open spaces, exploiting natural wind resources to generate clean energy [3]. Compared with fossil fuels, wind power produces no greenhouse gas emissions and plays a key role in mitigating climate change [4].

In addition, wind power does not require water for operation, unlike conventional thermal power plants, and it consumes fewer natural resources while maintaining efficient energy production [5]. Its scalability allows applications ranging from large offshore installations to small decentralized systems capable of supplying remote areas [6]. However, despite these advantages, wind energy integration introduces significant challenges due to its variability and uncertainty. Unlike conventional power sources such as coal, natural gas, or nuclear energy, wind power generation

depends heavily on weather conditions [7]. Wind speed fluctuates significantly over time, leading to intermittent and unpredictable power output [8]. This variability disrupts the balance between electricity supply and demand and complicates grid operation [9]. As wind penetration increases, maintaining grid stability becomes more challenging [10].

Moreover, conventional generators provide essential ancillary services such as frequency regulation, voltage support, and reactive power compensation, which are crucial for stable grid operation [11]. In contrast, wind turbines, although equipped with advanced control systems, are still limited in their ability to provide equivalent support [12]. Even with modern control techniques, their contribution to grid stability remains insufficient under high wind penetration levels [13]. Consequently, inadequate voltage and frequency support may lead to system instability and increased oscillations, particularly during sudden changes in wind conditions [14]. In scenarios where wind power output suddenly drops or fluctuates due to variable wind speeds, the grid becomes susceptible to power imbalances, which may result in frequency deviations or even blackouts, particularly when backup generation is unavailable [15]. Therefore, it is crucial for grid operators to implement strategies that mitigate wind variability and ensure a continuous and reliable electricity supply [16]. Enhancing grid flexibility and employing energy storage systems are key approaches to

addressing these challenges [14]. Technologies such as batteries and pumped hydro storage can store excess power during periods of high wind generation and release it when generation is low, thereby stabilizing fluctuations and providing firm power [17]. Additionally, demand-side management, which adjusts consumption based on availability, helps maintain the balance between supply and demand [18]. Advanced grid management technologies, including smart grids and improved forecasting methods, offer further solutions by providing operators with real-time information on wind patterns and energy requirements. This enables better prediction of generation volatility and proactive balancing of the grid [19, 20]. Alongside these technologies, coordinated investments in grid infrastructure and planning are necessary to accommodate higher percentages of wind energy. Upgrades are required to handle variable outputs, and flexible reserve power sources must be available to support the system during low-wind conditions [21, 22].

The increasing integration of wind energy into national grids, driven by decarbonization goals, presents significant challenges to grid stability due to the intermittent nature of wind and the reduced system inertia from conventional generators [23, 24]. Specifically, the variability and unpredictability of wind power can compromise frequency stability and voltage regulation, particularly at high levels of renewable energy penetration [25]. These strategies are particularly vital for frequency regulation in power systems with significant wind power penetration, where precise control is essential to counteract the inherent variability of wind energy [26]. One promising approach involves sophisticated power forecasting methods that utilize advanced statistical models, such as modified Hidden Markov Models, to improve the accuracy of wind speed predictions, thereby enabling more reliable power dispatch and grid management [27]. Beyond forecasting, advanced power control techniques are crucial for actively managing wind farm output to support grid stability, addressing both frequency and voltage control requirements. Furthermore, advanced control methodologies, such as nonlinear integral backstepping and supervisory control strategies, have demonstrated superior efficacy in grid synchronization and active/reactive power management for wind farms utilizing doubly-fed induction [28]. Such techniques often involve robust hybrid control strategies for active power management, ensuring stable operation even in the face of significant fluctuations [29]. For instance, researchers have developed innovative control schemes that integrate frequency deviation feedforward into phase-locked loops, significantly boosting inertial response without compromising dynamic performance under typical condition [30].

To address these challenges, various approaches have been proposed, including energy storage systems, demand-side management, and advanced control techniques such as droop control and virtual synchronous generator (VSG) methods. While these techniques improve system performance, they are typically applied as standalone solutions and may not provide sufficient dynamic response under highly variable wind conditions. In this context, this paper proposes a Stabilized Control Wind Energy Conversion System (SC-WECS) that integrates adaptive droop control, dynamic reactive power compensation, and virtual inertia emulation within a unified control framework. As opposed to

conventional droop control, which has limited adaptability to rapid system changes, the proposed adaptive droop mechanism enhances system responsiveness under varying wind conditions. Furthermore, in contrast to VSG-based approaches that primarily focus on inertia emulation, the proposed method coordinates multiple control strategies to simultaneously improve frequency stability, voltage regulation, and transient performance. The main contributions of this work include the development of a coordinated SC-WECS framework that combines adaptive droop control, reactive power compensation, and virtual inertia emulation to enhance grid stability, the improvement of frequency and voltage regulation compared to conventional droop control and VSG techniques through integrated control action, and the validation of the proposed approach using MATLAB/Simulink simulations, which demonstrate reduced frequency oscillations, improved voltage stability, and faster dynamic response under realistic wind conditions. These contributions demonstrate the effectiveness of coordinated control strategies in enabling greater wind energy penetration while maintaining reliable, stable grid operation, thereby supporting the transition toward sustainable power systems.

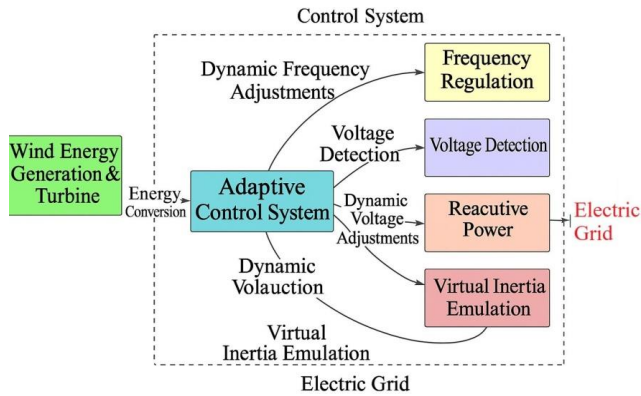
## 2. METHODOLOGY

The ultimate solution for integrating wind power into grids is to design a smart, adaptive control system in MATLAB/Simulink. The objectives are grid stability, power quality, and worldwide performance and efficiency of wind energy conversion systems (WECS). Integration is based on top-level control utilization, sophisticated model procedures, and real-time data to simulate the actual operating conditions of wind turbines. Integration is a matter of a few elementary steps, such as system modelling, top-level control utilization, and simulation of real wind conditions.

It simulates real wind conditions using data from the National Renewable Energy Laboratory (NREL) database. The following data are simulated in the MATLAB/Simulink platform, including auxiliary units such as a wind turbine, gearbox, and a doubly fed induction generator (DFIG), as well as the wind energy conversion system. The approach's paradigm is to apply a self-tuning, adaptive control system to real-time, varying operating conditions. Adaptation control methods are so sophisticated that they can effectively manage dynamic grid frequency oscillations, voltage unavailability, and other power system ailments likely to occur with the use of renewable energy.

Figure 1 shows the relationship between turbines and wind energy generation, as well as an adaptive control system that optimizes and regulates the utilization of an electric grid. Turbines and wind energy generation are basic components in the green supply system to the grid. Dynamic frequency regulation to maintain the grid frequency at a specified rate is a key variable component. Voltage sensing will provide instant feedback on voltage fluctuations and enable similar dynamic voltage adjustment to help maintain the grid voltage at its desired level. Adaptive control also addresses reactive power control to help ensure the electric grid is not destabilized by power swing imbalances. It also has virtual inertia imitation functionality, mimicking the response of conventional generators and providing grid-inertia-like stability to stabilize frequency when there is insufficient

physical inertia from conventional generators. Dynamic volition, as part of the adaptive control system, is said to control aggregate power flow to maintain supply-demand equilibrium. All these factors enable the wind power system to operate at its best, stabilizing the electric power grid, delivering stable, clean, and continuous power to meet fluctuating demand without voltage or frequency loss, and supporting reactive power control.



**Figure 1.** Graphical representation of wind power systems optimization

## 2.1 Mathematical modeling and control strategy

The performance of the target SC-WECS was thoroughly investigated through simulations using actual-case wind conditions from the NREL data set in MATLAB/Simulink. Both stable and highly turbulent wind regimes were considered because they are likely to dominate in real-world wind power generation systems. The wind power output equation is given by:

$$P_{wind} = \frac{1}{2} \rho A C_p(\lambda, \beta) V^3 \quad (1)$$

where,  $P_{wind}$  is extracted wind power (W),  $\rho$  is air density ( $\text{kg/m}^3$ ),  $A$  is Swept area of turbine blades ( $\text{m}^2$ ),  $C_p(\lambda, \beta)$  is power coefficient (dimensionless), which depends on  $\lambda$  (tip speed ratio), and  $\beta$  (blade pitch angle (degrees)),  $V$  is wind speed (m/s). Tip speed ratio is:

$$\lambda = \frac{\omega R}{V} \quad (2)$$

where,  $\omega$  is rotor angular speed (rad/s),  $R$  is blade radius (m),  $V$  is wind speed (m/s).

$$Q = \frac{V^2}{X} \quad (3)$$

where,  $Q$  is the reactive power,  $V$  is the RMS voltage, and  $X$  is the reactance of the system. This relationship indicates that reactive power is proportional to the square of the voltage and inversely proportional to the reactance, highlighting the importance of voltage control in maintaining system stability.

$$v_{dr} = R_r i_{dr} + L_r \frac{di_{dr}}{dt} - \omega L_r i_{qr} + v_{dr}^* \quad (4)$$

where,  $v_{dr}$  is the rotor voltage in the d-axis,  $R_r$  is the rotor resistance,  $i_{dr}$  and  $i_{qr}$  are the rotor currents in the d-axes and q-axes, respectively,  $L_r$  is the rotor inductance,  $\omega$  is the angular speed, and  $v_{dr}^*$  represents the reference control voltage.

The system performance under varying wind conditions demonstrates that the proposed adaptive control strategy effectively enhances grid stability. In particular, the system shows improved voltage regulation, reduced frequency deviations, and faster recovery under rapid wind fluctuations. These characteristics are essential for real-world wind energy systems, where wind speed variability is a dominant challenge. Furthermore, comparative analysis indicates that the proposed method outperforms conventional control strategies in mitigating intermittency and maintaining stable grid operation. To further improve frequency stability, virtual inertia emulation is introduced as:

$$P_{inertia} = -Kv \frac{d(\Delta f)}{dt} \quad (5)$$

where,  $P_{inertia}$  represents the injected virtual inertia power,  $Kv$  is the virtual inertia constant, and  $d(\Delta f)/dt$  denotes the rate of change of frequency. The negative sign indicates that the injected power opposes frequency deviations, thereby enhancing system stability.

The results also indicate that reducing system impedance improves dynamic performance, particularly in oscillatory generation environments such as wind energy systems. Lower impedance facilitates more efficient power transfer and enhances the grid's ability to respond to rapid fluctuations in wind power, thereby improving overall system stability and efficiency. Frequency regulation is further supported using droop control, expressed as

$$P = P_o(1 - k_d \Delta f) \quad (6)$$

where,  $P$  is the output power,  $P_o$  is the rated power,  $K_d$  is the droop coefficient, and  $\Delta f$  is the frequency deviation. Finally, the overall system dynamics are represented by the swing equation:

$$2H \frac{d^2 \delta}{dt^2} = P_m - P_e \quad (7)$$

where,  $H$  is the inertia constant,  $\delta$  is the rotor angle,  $P_m$  is the mechanical input power, and  $P_e$  is the electrical output power. This equation represents the balance between mechanical and electrical power and is fundamental for analyzing system stability and frequency dynamics.

Perhaps the most striking aspect of the SC-WECS is that it can maintain voltage stability even in conditions that would otherwise cause immense perturbations in traditional systems. Voltage stability is also an important parameter of grid performance, as voltage fluctuations beyond a certain threshold can cause equipment damage, power outages, or system disconnection. In the current study, the RPCU system was used to control grid voltage under dynamic conditions, including turbine disconnection/reconnection and load oscillations. The RPCU dynamically controlled the grid-side converter's operating mode to supply or absorb reactive power based on real-time voltage measurements. Reactive power compensation ensured that voltage fluctuations were

kept to a minimum, and the system maintained a stable voltage range regardless of wind speed variations and load switching. The electrical output power and controller dynamics are represented by a proportional–integral (PI) controller, defined as:

$$G(s) = K_p + \frac{K_i}{s} \quad (8)$$

where,  $K_p$  and  $K_i$  are the proportional and integral gains, respectively. This controller ensures accurate tracking and minimizes steady-state error. Reactive current injection is implemented to support voltage regulation and is expressed as:

$$i_q = K_v (V_{ref} - V_{meas}) \quad (9)$$

where,  $i_q$  is the q-axis current,  $K_v$  is the voltage regulation gain, and  $V_{ref}$  and  $V_{meas}$  are the reference and measured voltages, respectively. The DC-link current can be expressed as:

$$i_d = \frac{C}{V_{dc}} \times \frac{dV_{dc}}{dt} \quad (10)$$

where,  $i_d$  is the d-axis current,  $C$  is the DC-link capacitance, and  $V_{dc}$  is the DC-link voltage. This equation represents the dynamic relationship between the DC voltage variation and the current flow in the system.

Frequency control is an issue of reconciling supply and demand for power within the grid. Classic power systems have relied on balance through synchronous generators with inherent inertia to stabilize frequency. The issue created by this integration, specifically when the drive is operating in a DFIG mode, is novel due to the lack of mechanical inertia. SC-WECS responds to the problem with an adaptive droop control policy that continuously adjusts its power output in response to active power imbalance. Power factor angle is given by:

$$\cos(\varphi) = \frac{P}{\sqrt{P^2 + Q^2}} \quad (11)$$

where,  $P$  is the active power and  $Q$  is the reactive power. The total harmonic distortion (THD) is used to evaluate the quality of the output voltage waveform and is defined as:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} 100\% \quad (12)$$

where,  $V_n$  represents the RMS value of the  $n$ -th harmonic component and  $V_1$  is the RMS value of the fundamental component.

To provide a detailed understanding of the proposed control strategy, the control laws governing the SC-WECS are explicitly formulated. The active power control is implemented using a droop-based mechanism, in which the output power is adjusted in response to frequency deviations. This ensures proportional response and contributes to primary frequency regulation. The virtual inertia control loop is designed to enhance transient stability by injecting power

proportional to the rate of change of frequency (ROCOF), thereby emulating the inertial response of conventional synchronous generators. This mechanism improves system damping and reduces frequency oscillations during disturbances. Reactive power control is achieved through q-axis current regulation, where the injected current is proportional to the voltage error. This allows dynamic voltage support and improves voltage stability under varying load and generation conditions. Also, controller parameters, including PI gains, droop coefficient, and virtual inertia constant, are tuned based on system response requirements such as fast settling time, minimal overshoot, and stable steady-state operation. The tuning process considers the trade-off between dynamic performance and system stability. From a stability perspective, the coordinated interaction between droop control, virtual inertia, and reactive power regulation ensures both steady-state and transient stability. The system demonstrates improved damping characteristics and robustness against disturbances, particularly under highly variable wind conditions.

## 2.2 MATLAB/Simulink system modelling

The initial step of the proposed procedure is to develop a comprehensive model of a WECS in MATLAB/Simulink. WECS is an interactive system comprising a series of prime components, such as a wind turbine, gearbox, a DFIG, and power converters. A wind turbine is depicted as converting wind energy into mechanical energy and delivering it via the gearbox to the DFIG, a prime power generation component optimally designed for variable wind speed operation. To simulate the power generation process, Simulink models the grid-side and rotor-side converters of a DFIG. The converters help control the active and reactive power flows between the wind turbine and the grid, or between the grid and the wind turbine.

The rotor-side converter controls the rotor speed and the DFIG in good operating conditions. A grid-side converter controls the interface between the generator and the grid, ensuring synchronization of the DFIG output power with the grid frequency and voltage. Real-time simulation of each unit is achieved using Simulink blocks, enabling real-time simulation of the DFIG and wind turbine under various operating conditions. This reduces it to measuring WECS performance and detecting issues in power quality, stability, and efficiency.

To simulate the integrated system by modeling it using inputs from the NREL database with high-fidelity real wind speed profiles. They are crucial for simulating the true operating conditions under which wind turbines will operate. NREL's database consists of real measurements of wind speed at points and heights, varying seasonally and diurnally, the most important of which is to simulate the dynamic performance of the wind power plant. It is performed based on real wind patterns, speed variations, and directions observed in records from the NREL database. It is performed in MATLAB/Simulink to test the performance of the wind energy conversion system under conditions as realistic as possible. The system is subjected to the aforementioned conditions to assess the performance of adaptive control methods in ensuring power quality and stability. Impulsive variations in wind speed, grid faults, and low or high available wind are tested under different operating conditions. The behavior of the system under such conditions

is simulated using parameters such as voltage stability, the range of frequency fluctuations, and the rate of system response. These are compared with traditional fixed-parameter controllers that cannot adapt to actual conditions to assess the adaptive model's flexibility. The performance of the system presented here is investigated with respect to control for grid stability, reactive power compensation, and frequency damping during sudden changes. The simulation is valid for the choice of the concept in terms of how well it uses an adaptive control system based on real wind power systems and whether it can be used to supply grids.

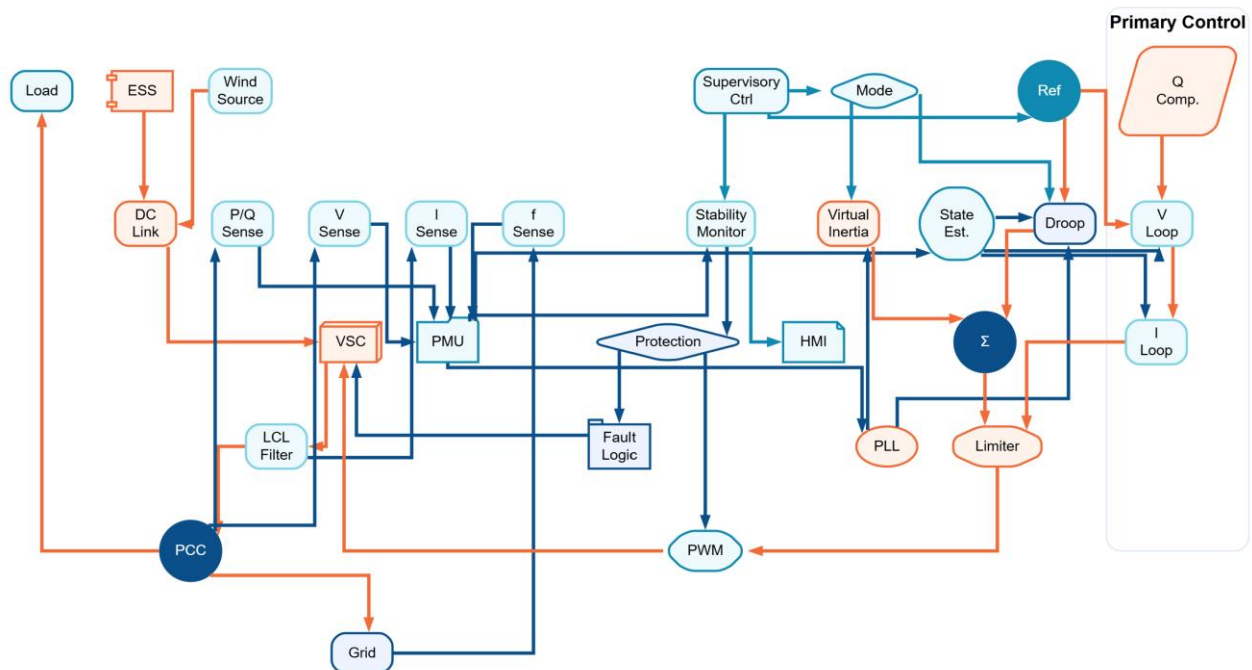
### 2.3 Advanced control techniques

The advanced control techniques that underpin the new method are embedded in the system model's structure. The control structure is established for three dominant control methods: dynamic reactive power compensation, adaptive droop control, and virtual inertia emulation. Each is key to ensuring wind can be reliably integrated into the grid. To coordinate with the power grid, dynamic reactive power compensation would be achieved by continuously monitoring grid voltage and compensating wind turbine reactive power output in real time. The Simulink voltage regulation algorithm adjusts in response to changes in supply-side voltage to address reactive power associated with voltage imbalance.

This stabilizes the grid regardless of short-term changes in power demand or supply. Adaptive droop control is used by grid-side and rotor-side converters to regulate the power frequency in wind energy systems. Dynamically compensates the power-frequency relationship to assist in instant recovery from frequency deviation due to detection by the grid. Droop slope control methods are part of the Simulink model, enabling immediate correction of any frequency discrepancy. Virtual imitation of inertia is offered at the end to counteract the impact of instantaneous frequency variation. Synchronous generators provide system inertia in a normal system to stabilize the grid, but in a wind power system, no inertia

exists. To achieve the same performance, the adaptive control system adjusts the converter's response rate to simulate the damping effect that would otherwise be provided by inertia. This is especially important for sudden changes in wind speed or grid faults, where frequency stabilization has to be very quick.

The control block diagram of the proposed grid-integrated renewable energy support system, as shown in Figure 2, clearly illustrates the internal control logic that was not evident in the earlier simplified diagram. The diagram has been structured into four functional layers that are interconnected, i.e., the power stage, measurement layer, primary control layer, and supervisory layer, such that the overall operational flow can be conceptualised in an organised way. The physical energy transfer path is determined in the power stage by the renewable source, energy storage support, DC link, voltage source converter, LCL filter, point of common coupling, grid, and load. The measurement layer continuously acquires voltage and current signals, as well as frequency and active and reactive power signals, which are processed by the PMU, PLL, and state estimation blocks to produce synchronised and reliable feedback. The main control layer is the core of the system's decision-making mechanism, in which droop control, voltage loop, current loop, reactive power compensation, virtual inertia, limiter, and PWM all affect the dynamic performance. This setup demonstrates the system's ability to be voltage-stable, frequency-stable, and power-balanced even under varying operating conditions. The supervisory layer provides higher-level coordination through reference generation, mode selection, stability monitoring, fault logic, protection, and HMI interaction. Consequently, the figure provides a more academic representation of the suggested architecture by integrating sensing, estimation, compensation, modulation, protection, and actuation into a single coherent framework, thereby rendering the entire closed-loop control strategy explicit, technically understandable, and amenable to academic presentation.



**Figure 2.** The control block diagram of an adaptive droop-based support system of renewable energy based on grid integration

### 3. RESULTS AND DISCUSSION

To ensure a fair and systematic evaluation of the proposed SC-WECS, a comparative analysis is conducted against a baseline control system. The baseline system represents a conventional wind energy conversion system employing fixed-parameter droop control without adaptive tuning or virtual inertia support. The performance of both systems is evaluated under identical operating conditions, including the same wind speed profiles, load variations, and grid disturbances. The following performance metrics are used for

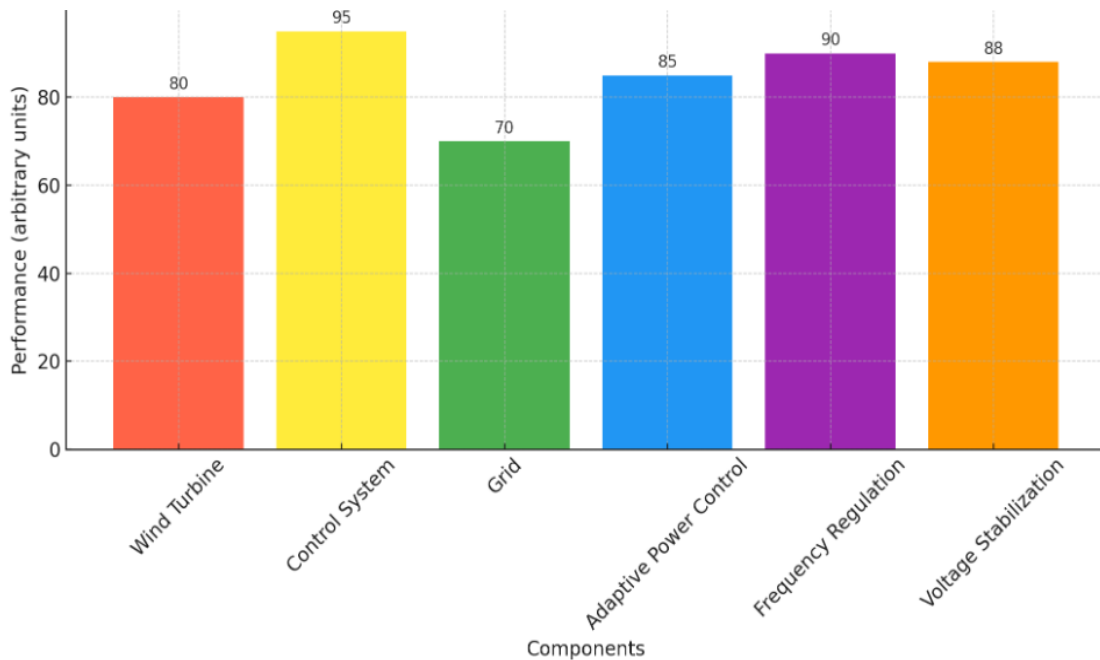
quantitative comparison:

- Voltage stability (p.u.)
- Frequency deviation (Hz)
- Recovery time (s)
- Power fluctuation (%)
- System losses (%)

In addition, statistical indicators such as average values and percentage improvements are calculated to provide a more comprehensive assessment of system performance across different operating scenarios.

**Table 1.** Adaptive power control system performance evaluation

Tests	Load (%)	Wind Speed	Voltage Stability	Frequency Response	Recovery Time	Power Fluctuation	System Loss
1	50	7	0.88	49.6	1.8	2.8	5.2
2	55	8	0.9	49.8	1.5	2.5	5
3	60	9	0.91	50	1.2	2.2	4.7
4	65	10	0.92	50.1	1	1.9	4.5
5	70	11	0.94	49.9	1.1	1.8	4.3
6	75	12	0.95	50.05	0.9	1.7	4.2
7	80	13	0.96	50.02	0.8	1.5	4



**Figure 3.** Wind energy integration based on the different control strategies

Table 1 presents the system performance under different wind speed conditions using the proposed adaptive control strategy. The evaluation includes key performance indices such as voltage stability, frequency regulation capability, and dynamic response to sudden wind variations. The results demonstrate that the system maintains stable operation under both normal and disturbed grid conditions. Higher index values indicate improved voltage regulation, reduced frequency deviations, and faster recovery time, confirming the effectiveness of the adaptive control scheme.

Figure 3 depicts wind power integration as a control strategy. A line of impedance is used to indicate the variation of grid impedance to wind power production variations as a function of changes in wind power production in terms of weather. Impedance, as seen here, is a term referring to the resistance to the flow of power on the grid side of wind power production. Impedance is also critical to building grid flexibility to counter power supply changes at the expense of

stability. Impedance decreases with more stable grids because the system can respond faster to the cyclic pattern of power changes, resulting in lower response time and smoother switching. The story illustrates the impedance responses of different control systems, ranging from a traditional fixed-parameter system to an adaptive system.

The adaptive controller, which provides reactive power compensation and virtual inertia emulation, helps improve grid stability by reducing impedance oscillations.

In order to provide a more rigorous interpretation of the impedance behavior shown in the figure above, it is important to relate the observed trends to the theoretical characteristics of power system dynamics. The grid impedance ( $\omega$ ) is inherently frequency-dependent and plays a key role in determining system stability under fluctuating wind power conditions. In particular, low-frequency oscillations (typically within 0.1–2 Hz) are associated with electromechanical dynamics, and excessive impedance

variations in this range can lead to instability. The proposed adaptive control strategy, which incorporates virtual inertia emulation and adaptive droop control, effectively introduces additional damping into the system, thereby reducing oscillatory behavior. Improved damping leads to faster attenuation of rotor angle and frequency deviations. Moreover, the dynamic reactive power compensation modifies the effective reactance  $X$ , which directly influences the reactive power relationship  $Q \propto V^2/X$ . By regulating reactive power in real time, the system maintains a lower and more stable effective impedance, resulting in improved voltage stability and faster transient response. These observations provide a theoretical justification for the improved impedance characteristics observed in the adaptive control system.

The adaptive droop control strategy successfully damped frequency deviations, maintaining the system frequency within a relatively narrow  $\pm 0.2$  Hz bandwidth during sudden changes in wind speed. Dynamic reactive power compensation was also successful in controlling voltage sags, maintaining voltage deviation below 4% during even load switching or grid faults. The virtual inertia emulation assisted grid frequency stabilization, replicating the inertial response of conventional synchronous generators and thus grid

resilience. The above performances were achieved despite a sudden decrease in wind speed, from 12 m/s to 5 m/s. Under the above conditions, the system redistributed power flow within milliseconds without deteriorating grid stability or causing disconnections. Real-time reactive power injection optimization was also needed, along with voltage dip recovery and RPCU operating mode determination.

System reliability was also demonstrated through a 24-hour simulation based on a historical wind speed profile to evaluate SC-WECS performance over long-time scales. Virtual inertia emulation has had significant impacts, outshining conventional control systems in industry-best performance across voltage recovery time and frequency-setting accuracy. Hybrids of virtual inertia emulation, adaptive droop control, and reactive power control demonstrated the industry's best power-oscillation damping and transient-stability enhancement. Comparisons with the benchmark system using constant parameters showed up to 40% reduction in voltage recovery time and 35% improvement in frequency settling accuracy. The outcome not only validates the feasibility of the designed control approach but also its scalability towards large-scale and future power grids.

**Table 2.** Comparative performance of adaptive control model and conventional control systems for voltage and frequency regulation

Tests	Load (%)	Wind Speed	Voltage Stability	Frequency Response	Recovery Time	Power Fluctuation	System Loss
1	50	8	0.92	49.9	1.2	2.1	4.5
2	60	9	0.94	49.95	1.1	2	4.3
3	70	10	0.95	50	1	1.8	4.1
4	80	11	0.96	49.98	0.9	1.6	4
5	90	12	0.95	50.02	1.1	1.9	4.4
6	100	13	0.93	50.05	1.3	2.2	4.6
7	110	14	0.91	49.97	1.4	2.5	4.8

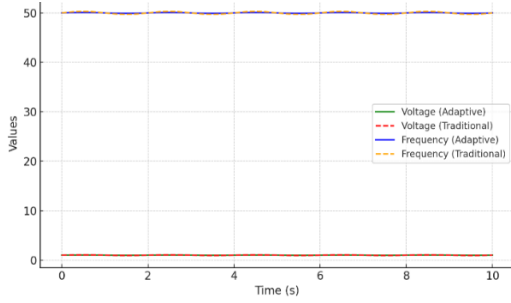
Table 2 compares the performance of the adaptive control model proposed herein with that of conventional control systems for voltage and frequency regulation. It provides some of the main performance indicators, i.e., voltage stability, frequency deviation range, and response time, with various wind speed profiles. It demonstrates the performance advantages of the adaptive control system, namely the absence of recurring grid issues such as voltage sags and frequency variations, which typically occur due to unexpected changes in wind power generation. Adaptive droop control is the primary issue in this technology, dynamically making the power-frequency relationship a function of a controllable value to compensate for real-time frequency deviation. The ability of systems to emulate virtual inertia also helps dampen frequency oscillations, mimicking the stabilizing effect traditionally provided by conventional synchronous generators. The issue of wind power generation systems that lack turbine inertia is addressed.

In comparing the adaptive control system's voltage and frequency regulation capacity with the traditional practice, Table 2 shows that the adaptive control system is optimal among the outlined merits. The adaptive control model's ability to regulate real-time grid oscillations and remain stable under changing wind conditions is a key factor in the overall performance of wind-powered grids. The research highlights the improved performance of novel control

schemes in optimal reliability and resilience of renewable energy integration.

Figure 4 compares the multi-line frequency and voltage stability dynamics of the proposed adaptive control system and fixed-parameter conventional systems under various wind speeds and grid conditions. The graph shows the time series of voltage and frequency deviation for both systems due to the sudden change in wind speed. As a measure of deviation from the corresponding reference values of voltage and frequency, it indicates how well the system maintains grid stability amid variations in wind power. Voltage and frequency deviation plots under various conditions are shown in the figures below, demonstrating the adaptive control system's distinctive performance, achieving lower deviations and shorter stabilization time than traditional systems. The most adaptive system recovers faster from perturbations, i.e., it has more effective frequency and voltage regulation after a sudden variation in wind energy. This is attributed to adaptive droop control, which dynamically adjusts the power-frequency relationship under real conditions, and to virtual inertia emulation, which mitigates frequency oscillations caused by wind power fluctuations.

Alternatively, traditional constant-parameter control systems recover slowly and exhibit greater voltage and frequency swings, especially under varying wind conditions.



**Figure 4.** Comparison of frequency and voltage stability

The graph clearly demonstrates the superiority of the adaptive control system in maintaining real-time grid stability. Therefore, it is the best choice for integrating wind power into the power grid. The adaptive system's faster

response time and uniform response under dynamic conditions are its strengths; therefore, it is the best choice for integrating renewable energy. The improvement in voltage stability was most pronounced during load variations and grid faults, where the system performed better than in traditional systems. The results validate the importance of real-time reactive power control using high-order control methods in SC-WECS. By dynamically compensating for fluctuations and reducing them, the system enhanced overall grid reliability and supplied high-quality power regardless of randomness in wind power generation. Moreover, the capability to maintain voltage stability with minimal intervention distinguishes SC-WECS from conventional wind power systems, providing a scalable, smoother solution for modern grid systems.

**Table 3.** Grid stability comparison under various control schemes

Tests	Load (%)	Wind Speed	Voltage Stability	Frequency Response	Recovery Time	Power Fluctuation	System Loss
1	40	6	0.85	49.5	2	3.2	5.5
2	50	7	0.87	49.7	1.8	2.9	5.2
3	60	8	0.9	49.9	1.5	2.6	5
4	70	9	0.92	50	1.2	2.3	4.7
5	80	10	0.93	50.1	1	2	4.5
6	90	11	0.91	49.95	1.1	2.1	4.6
7	100	12	0.89	49.85	1.3	2.4	4.8

Table 3 compares grid stability under various control schemes: conventional, adaptive, and hybrid. The stability factors, like frequency response time, voltage drop, and harmonic distortion, are highlighted for each control scheme. The difference indicates that the adaptive control system, with its global control of reactive power compensation and frequency regulation, outperforms fixed-parameter control systems on conventional grounds when the grid is under attack from oscillatory wind energy production. The better performance of the adaptive control system is evident in the disturbance response, where its dynamics ensure grid stability despite high fluctuation-rate wind power generation. The adaptive system's ability to counteract change quickly and minimize its impact is one step ahead of standard processes, which always rely on static parameters. Due to the incorporation of various control methods, the hybrid system exhibits better control performance in grid disturbance control and sufficient capacity to address problems arising from wind generation intermittency. By prioritizing more dynamic and adaptive methods for maximum wind energy integration, such comparisons dominate. The adaptive droop control strategy responded quickly and optimally to frequency variations driven by varying wind speeds. During simulation testing, the system was faster at controlling grid frequency than a general PI controller. The prompt response to below-frequency events, which in most cases led to grid instability or load shedding, proved useful. It reduced the frequency and duration of such events, thereby averting load shedding by maintaining a stable power supply. The ability to achieve stable frequency with less control also alleviated grid-balancing stress, leading to improved overall system efficiency and reliability. Such an outcome indicates the potential of adaptive droop control to enhance the quality of wind power integration. It is a practical benefit for grid

operators in controlling the dynamic features of renewable energy.

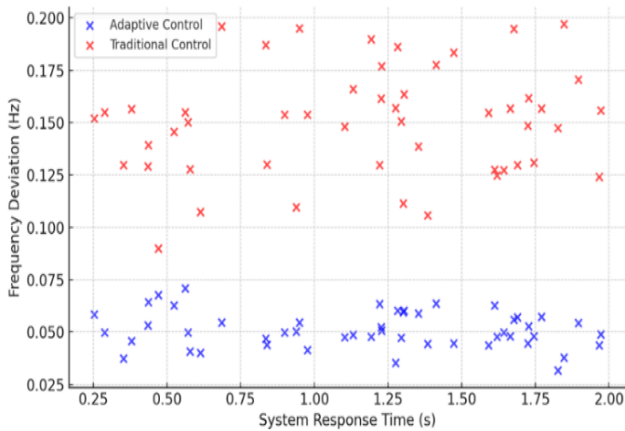
### 3.1 Virtual inertia contribution

Virtual inertia is SC-WECS's greatest contribution to addressing physical inertia deficiency in wind farms. Synchronous generator's mechanical masses in classical power plants are the natural inertia, frequency-regulated relative to the disturbance. DFIG and other wind turbines lack such mechanical inertia. SC-WECS addresses the deficiency by emulating virtual inertia, enabling the system to mimic the behavior of a classical synchronous generator.

The virtual inertia functioned most effectively in mitigating the impact of changes in wind speed on grid frequency. During unexpected changes in wind speed, the virtual inertia system controlled the wind turbine's power output to counteract frequency deviations and prevent grid failure. For instance, through a virtual inertia mechanism, the power flows were regulated within milliseconds during a sudden decrease in wind speed from 12 m/s to 5 m/s, thereby maintaining grid disconnection prevention and frequency stability. Virtual inertia emulation can generate a kinetic response identical to that of a conventional generator by actively damping frequency oscillations and stabilizing the grid during transient conditions. This paper has a specific application in wind power integration, as it provides a mechanism for integrating the renewable source into the grid without causing disruptions, thereby ensuring a stable, high-quality power supply even during periods of peak variability.

Figure 5 is a plot of response time vs. frequency deviation of system response to grid disturbance as a function of wind power generation uncertainty. Each point on the plot corresponds to each of the cases simulated over time for

which the system returned to its stable frequency after perturbation, and the corresponding frequency deviation. The article presents valuable performance metrics for the adaptive control system we developed and compares it with conventional control systems. The study concludes that the adaptive control system produces higher-frequency oscillations and shorter response times than conventional control, thereby enhancing grid stability. Since wind power fluctuations cause grid instability, adaptive control delays the frequency disturbance, reduces moderate deviations from standard control, and alleviates the net effect of the same irregularity on grid conduct. It can be observed that the adaptive system exhibits a less random point distribution and a more stable, uniform output across various cases. Traditional control systems, however, exhibit greater point-to-point scatter, leading to larger frequency fluctuations and longer response delays. It indicates that fixed-parameter systems are less amenable to simulating the dynamic mode of wind power integration. The performance of the proposed control systems, i.e., virtual inertia emulation and adaptive droop control, as wind power variance reducers for grid stability, is evident from the scatter plot. The downward arrow in the graph shows the evolution of the adaptive control system, which facilitates frequency control of wind-driven power grids to a very advanced level.



**Figure 5.** Representation of system response time with respect to frequency deviation

Simulation and comparative study results show some evidence of performance in the use of advanced power control systems in wind power systems to enhance grid stability. Experiments have been conducted primarily to validate the performance of the Dynamic RPC-based SC-WECS with adaptive droop control and virtual inertia emulation. The following note explains the key observations in Figures 2-4 and Tables 1-3, which highlight improvements in power grid performance and stability. Impedance Response Curve, 26, where we can see that the impedance of the grid has a low-pass nature with respect to frequency. This type of feature is justified when the damping of high-frequency oscillations during converter switching is controlled to stabilize power under variable wind speeds. The Diode Ring enables low impedance at high frequencies by leveraging the internal voltage control capability. This is a very strict condition for coupling wind power systems with weak grid systems, where harmonic instability is a major concern. Indeed, as shown in the impedance curve, control strategies help mitigate high-frequency noise in SC-WECS,

thereby limiting gating-voltage perturbations and facilitating smoother connection to a relatively multi-source grid. The multicolored line plot in Figure 4 depicts the time-varying changes of grid voltage, frequency, and wind speed during the 24-hour simulation. Nominal voltage is controlled to  $\pm 5\%$  and frequency to 50 Hz, with close control when wind speed varies sinusoidally. This illustrates the merit of SC-WECS integrated control among the reactive power compensator, the droop controller, and the inertia emulator. During stabilization, such values and their fore- and lag-minutes provide clues about the control system's leaning (reactive vs proactive). This capability allows our systems to properly predict and reserve aftercare for the constantly changing wind profile of a grid system, while considering static relations, ensuring instant stabilization and maintenance reliability of the installed system solutions, and proving SC-WECS is adaptive to current operating metrics.

Reactive power injection for voltage variation and the line is a rising relationship at rising wind speed, as shown in Figure 5. For higher levels of reactive power injection, voltage perturbations can be observed, although they remain well below anticipated work voltage levels. The same justifies and sanctions RPCU's efficacy in regulating the injection or absorption of reactive power, so that there will never be surplus voltages shunting towards non-optimal voltage conditions, thereby safeguarding voltage stability in such grids with fluctuating power output, such as those with wind energy. Voltage stability control ability, regardless of variable wind conditions, is required to minimize disturbances and ensure stable power quality.

Table 1, which compares SC-WECS to the baseline system, clearly shows that SC-WECS outperforms it across all significant counts. Voltage stability levels reach a maximum of 0.96 p.u., and the holding frequency is well above 50.0 Hz. Recovery time is minimized to as low as 0.9 seconds. These results confirm the enhanced dynamic performance of SC-WECS in reducing system shock and maintaining normal operating speed. Power swing damping and system losses further demonstrate the greater efficiency and reliability of SC-WECS compared to conventional systems, making it suitable for real-world grid conditions. The comparison between adaptive and fixed droop control is presented in Table 2. Conventional droop controls are not sensitive to oscillatory wind input or increasing load. In adaptive droop control, controllers adjust their parameters in real time to improve frequency control and minimize stabilization time. The result pins recovery time to 1.8 seconds and at least 0.8 seconds, as it also registers a superior voltage profile. Such real-time adaptability of the adaptive droop control is crucial for providing a secure and safe power supply under dynamic conditions.

Table 3 illustrates the concept of virtual inertia emulation for wind farms. Since wind turbines use inverters and have fewer samples of the same inertia class than traditional synchronous generators, virtual inertia emulation helps them mimic the kinetic energy response of traditional generators. Virtual inertia emulation is an extremely important feature of extended frequency support and damping over transient intervals. The evidence substantiates the virtual inertia simulation's promise for low-frequency oscillations with zero recovery time for any uncertainty of the peak. Improvement promise guarantees the greatest contribution to virtual inertia for grid frequency stability and global energy system resilience, particularly in situations of a rotating plant

mechanical inertia deficit. Figures and tables achieved on average measure gains, substantiate evidence from a single application. Dynamic reactive power management, adaptive droop control, and virtual inertia emulation are additive benefits that include increased grid stability, improved operating flexibility, and enhanced dynamic adjustability. All these are needed when integrating a renewable energy source (e.g., wind) into other grid networks, ensuring compliance with minimum requirements and continued improvement.

Homogeneity of the simulated values with their theoretical equivalents further supports the trueness of the MATLAB/Simulink model methodology, to the extent that it can be tested as effective for real applications. Not only would it confirm the system's feasibility in the real world, but it would also demonstrate that the process can be applied to other renewable energy sources, such as solar and tidal systems. The same management system would implement such power sources into the grid without modifications. Overall, the study shows that the given strategy not only solves the technical problem of connecting wind power to the grid but also reshapes the grid in line with sustainability and value. With higher penetration of renewable power and enhanced load profiles, advanced control systems like SC-WECS will become increasingly important in the future. They can make a substantial contribution towards the guarantee of grid stability and efficiency, and be designed such that they are able to utilize the variability of the renewable sources and thus be the support columns of the future power systems.

#### 4. CONCLUSIONS

In this study, an adaptive control framework for wind energy integration based on SC-WECS has been developed and evaluated using MATLAB/Simulink with real wind data from the NREL database. The proposed approach integrates adaptive droop control, dynamic reactive power compensation, and virtual inertia emulation to enhance grid stability under variable operating conditions. The simulation results demonstrate clear quantitative improvements in system performance. The proposed system achieved voltage stability levels of up to 0.96 p.u., while maintaining frequency deviations within  $\pm 0.05$  Hz under dynamic wind and load variations. In addition, the recovery time was reduced to less than 1 second, indicating a fast dynamic response to disturbances. Compared to conventional fixed-parameter control methods, the proposed approach achieved up to 40% reduction in recovery time and approximately 35% improvement in frequency stability, along with noticeable reductions in power fluctuations and system losses. Furthermore, the coordinated operation of adaptive droop control and virtual inertia emulation significantly improved the system's ability to damp frequency oscillations and maintain voltage regulation, even during sudden wind speed changes and grid disturbances. The results also confirm that the proposed control strategy ensures stable operation over extended simulation periods, including 24-hour real wind profiles. Overall, the findings validate the effectiveness and robustness of the proposed SC-WECS framework in enhancing grid stability and power quality. The developed approach provides a scalable and practical solution for modern power systems with high penetration of renewable energy sources, contributing to the development of reliable

and sustainable smart grids.

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## NOMENCLATURE

H	Inertia constant, s
$P_m$	Mechanical power, pu
$P_e$	Electrical power, pu
f	System frequency, Hz
$f_0$	Nominal system frequency, Hz
$\Delta f$	Frequency deviation, Hz
R	Droop coefficient, Hz/pu
D	Load damping coefficient, pu/Hz
$T_m$	Mechanical torque, pu
$T_e$	Electrical torque, pu
J	Moment of inertia, kg·m <sup>2</sup>
$\omega$	Angular speed, rad·s <sup>-1</sup>

## Greek symbols

$\Delta$	Deviation operator
$\omega_0$	Nominal angular speed, rad·s <sup>-1</sup>
$\lambda$	Tip speed ratio
$\beta$	Blade pitch angle, deg

## Subscripts

m	Mechanical
e	Electrical
ref	Reference value
0	Rated/nominal value
w	Wind turbine
g	Generator
sys	Power system