Engineering and Technology Journal e-ISSN: 2456-3358
Volume 11 Issue 09 September-2026, Page No.- 11536-11542
DOI: 10.47191/etj/v11i09.17, I.F. – 8.595

A Coordinated Q-V And P-F Droop Control of Grid-Forming Inverters for Enhanced Voltage and Frequency Stability

Godfrey Murairidzi GOTORA*[1], Mocanu VLAD [2], Blessed ZIYAMBE[3]
[1]Department of Electrical and Electronic Engineering, University of Zimbabwe, Harare, Zimbabwe
[2]Faculty of Electrical Engineering, Mircea cel Batran Naval Academy, Romania
[3]Faculty of Engineering, Bindura University of Science Education, Bindura, Zimbabwe

ABSTRACT: This script presents an adaptive coordinated Q-V and P-f droop control strategy for the grid-forming inverters operating in low inertia power systems. The proposed controller simultaneously regulates active power frequency and reactive power voltage dynamics through adaptive droop coefficients driven by real time disturbance indices. A complete nonlinear MATLAB model incorporating inverter dynamics, virtual inertia, LCL filtering, measurement delays and weak grid characteristics was developed and evaluated under three severe operating disturbances, a 30% load increase, 25% load reduction and 250% reactive power step, together with photovoltaic irradiance variations. Simulation results demonstrate that the coordinated controller maintains system frequency within approximately ± 0.3 Hz and voltage within ±0.05pu despite rapid power fluctuations. Compared with conventional fixed droop control, the adaptive strategy exhibits reduced frequency nadir deviation, smaller voltage dip, faster settling characteristics and lower integral error indices. Furthermore, weak grid analysis confirms that the controller preserves stable operation across a wide range of Short Circuit Ratios indicating improved robustness for renewable dominated distribution networks. The proposed coordinated droop framework therefore provides an effective solution for enhancing transient stability, grid resilience and autonomous voltage frequency support in future inverter-based power systems.

KEYWORDS: Grid forming, adaptive droop control, P-f droop, Q-V droop, voltage stability

1. INTRODUCTION

The increasing integration of renewable energy sources through power electronic converters is changing the dynamic behaviour of modern power systems (Mishra et al, 2025). As conventional synchronous generation is progressively complemented by inverter-based resources, grid forming inverters are receiving increasing attention because they can establish voltage and frequency refences and provide grid support functions without relying exclusively on an externally imposed waveform (Ding et al, 2025). However, the dynamic response of a grid forming inverter is strongly affected by variations in active and reactive power, renewable generation, measurement disturbances and changes in the electrical characteristics of the interconnected grid (Abdelwahab & Vokony, 2026). Droop control is widely used in grid forming inverter applications because of its relatively simple implementation and its ability to provide decentralised power sharing and voltage frequency regulation. In conventional droop control, the active power/frequency (P-f) and reactive power/voltage (Q-V) characteristics are generally defined using fixed droop coefficients (Kenyon et al, 2025). Although fixed coefficients provide predictable steady-state behaviour, the same control characteristic is maintained during both normal operating conditions and severe disturbances. Consequently, a controller selected for a nominal operating point may not provide the same dynamic performance when the system experiences substantial load changes, reactive power variations, renewable generation changes (Paulo et al, 2025). The limitation considered in this study is therefore the lack of operating condition-dependent adaptation in conventional fixed coefficient droop control. In particular, when the magnitude of frequency or voltage deviation changes, a fixed droop coefficient does not explicitly respond to the severity of the disturbance (Luo et al, 2025). This creates a need for a control mechanism that retains the simplicity of conventional droop control while allowing its control characteristics to adapt smoothly according to the instantaneous frequency and voltage conditions of the grid forming inverter (Ababas et al, 2026; Saimadhuri & Janaki, 2025). To address this limitation, this study proposes an adaptive coordinated P-f and Q-V droop control framework for the grid forming inverters. The proposed approach calculates frequency and voltage errors relative to their nominal values and converts their magnitudes into bounded disturbance indices using a hyperbolic tangent function. The resulting frequency and voltage disturbance indices are then used to modify the nominal P-f and Q-V droop coefficients dynamically. Thus, instead of maintain constant droop characteristics throughout the operating period, the proposed controller changes its effective droop coefficients as the magnitude of the disturbance changes. The adaptive coefficients are additionally constrained to predefined upper limits to avoid excessive modification of the nominal control characteristics (Anees et al, 2026).

The proposed framework is developed to evaluate the ability of adaptive droop control to improve the dynamic regulation of grid forming inverter frequency and voltage under multiple operating disturbances. The simulation considers an active power load increase, an active power load reduction, a reactive power disturbance and changes in photovoltaic generation. Measurement noise and first order power measurement dynamics are also incorporated into the simulation to represent non ideal measurement conditions (Huba et al, 2026). To establish the effectiveness of the proposed adaptation mechanism, its response is compared with a conventional droop controller in which the P-f and Q-V coefficient remain constant. The main contribution of this work is consequently the formulation and simulation-based assessment of a bounded, disturbance dependent adaptation mechanism for coordinating P-f and Q-V droop characteristics in a grid forming inverter. The proposed framework provides a systematic means of relating the instantaneous severity of frequency and voltage disturbances to the control. The study further establishes a quantitative evaluation framework through comparison with conventional fixed-coefficient droop control under multiple disturbance conditions (Wang et al, 2026). The remainder of the study is organised around the mathematical formulation of the adaptive droop mechanism, implementation of the grid forming dynamic model, definition of the disturbance scenarios, comparative simulation with conventional droop control and quantitative assessment of frequency and voltage performance.

2. MATERIALS AND METHODS

The proposed algorithm implements an adaptative coordinated droop control strategy for a three-phase Grid Forming inverter. Unlike conventional droop controllers that employ fixed droop gains, the methodology continuously adjusts the P-f and Q-V droop coefficients according to the real-time severity of frequency and voltage disturbances (Shahghalian et al, 2025). The controller integrates virtual inertia, first order measurement filtering, disturbance index estimation, adaptive gain scheduling and nonlinear state updating within a single simulation framework. The simulation begins by defining the electrical network, inverter, filter and grid parameters. It then models a 100kVA three phase grid forming inverter operating on a 400V, 50Hz Zimbabwean distribution system. The LCL output filter, DC-link capacitor, virtual impedance and grid impedance are initiated before the dynamic simulation begins. The grid strength is represented by the Short Circuit Ratio, allowing the same algorithm to investigate both strong and weak grids.

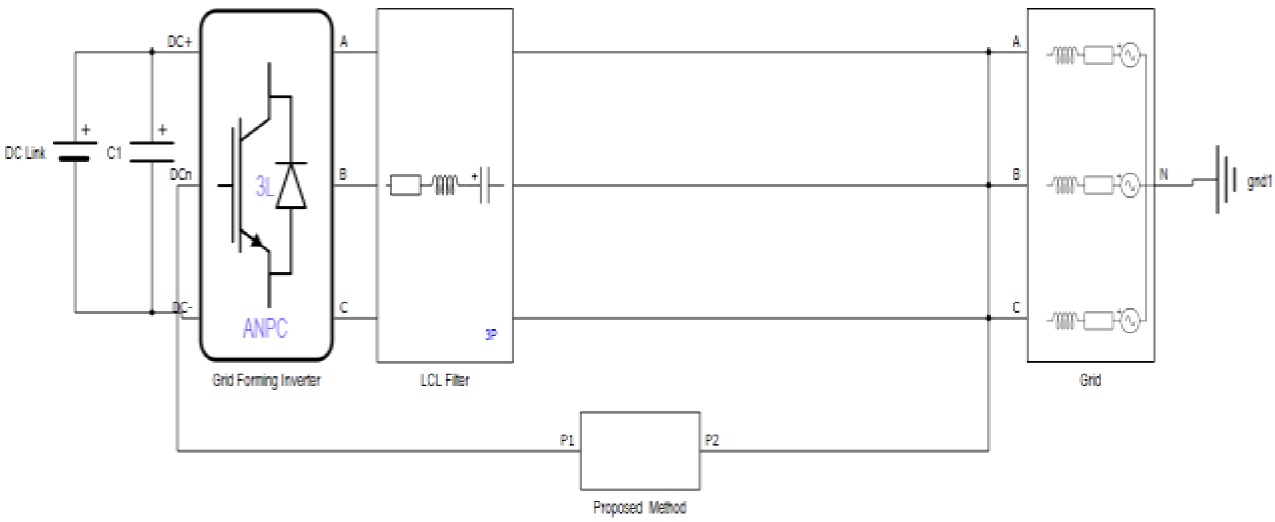

Figure 1 above showing the general circuit of the work simulation on MATLAB.

The system consists of a DC-link voltage source connected to a three-phase inverter through an LCL filter and grid impedance (Xi et al, 2025). The inverter side current is expressed as,

$$\mathbf{L_1 \frac{di_1}{dt} = v_{inc} - v_c - R_1 i_1} \quad (1)$$

The filter capacitor voltage is expressed as,

$$\mathbf{C_f \frac{dv_c}{dt} = i_1 - i_2} \quad (2)$$

The grid side current is expressed as,

$$\mathbf{L_2 \frac{di_2}{dt} = v_c - v_g - R_2 i_2} \quad (3)$$

Where i_1 is the inverter side current, i_2 is the grid side current, v_c is the filter capacitor voltage and v_g is the grid voltage. The conventional active power/frequency droop relationship is expressed as,

$$\mathbf{f = f_0 - m_p(P_{ref} - P_0)} \quad (4)$$

Where f_0 is the nominal frequency, P_0 is the nominal active power reference, m_p is the P-f droop coefficient. The conventional reactive power/voltage droop equation is expressed as,

$$\mathbf{V_{ref} = V_0 - n_q(Q - Q_0)} \quad (5)$$

Where V_0 is the nominal voltage, Q_0 is the reactive power reference and n_q is the Q-V droop coefficient (Abbas et al, 2026). The frequency error is defined as,

$$\mathbf{e_f(t) = f_0 - f(t)} \quad (6)$$

This represents the difference between the nominal frequency and the measured inverter frequency. Instead of using abrupt switching control, the method uses the hyperbolic tangent function to generate smooth disturbance indices. In addition, the frequency disturbance index is expressed as,

$$\mathbf{I_f(t) = tanh\left(\frac{|e_f(t)|}{e_{f,max}}\right)} \quad (7)$$

Where the disturbance index ranges from 0 to 1. This provides a smooth measure of frequency stress. The proposed method dynamically adjusts the frequency droop coefficient according to the disturbance level,

$$\mathbf{m_p(t) = m_{p0}[1 + k_f I_f(t)]} \quad (8)$$

Where m_{p0} is the base frequency droop coefficient, k_f is the frequency adaptation gain and $I_f(t)$ frequency disturbance index. The voltage droop coefficient is also dynamically adjusted as,

$$\mathbf{n_q(t) = n_{q0}[1 + k_V I_V(t)]} \quad (9)$$

Where n_{q0} is the base voltage droop coefficient, k_V voltage adaptation gain and $I_V(t)$ is the voltage disturbance index. To prevent excessive variation of the droop, limits are imposed. The proposed method incorporates a swing-equation based virtual inertia mechanism. The swing equation is expressed as,

$$\mathbf{2H\frac{d\omega}{dt} = P_{ref} - P - D(\omega - \omega_0)} \quad (10)$$

Where H is the virtual inertia constant, D is the damping coefficient, P_{ref} is the active power reference, P is the measured active power, ω is the instantaneous angular frequency and ω_0 is the nominal angular frequency. The discrete frequency is expressed as,

$$\mathbf{f(k+1) = f(k) + T_s\frac{d\omega}{dt}} \quad (11)$$

After substation the equation will become,

$$\mathbf{f(k+1) = f(k) + T_s\frac{P_{ref}(k) - P(k) - D[2\pi f(k) - 2\pi f_0]}{2H}} \quad (12)$$

The proposed continuous voltage controller uses the first order dynamic model after derivation is expressed as,

$$\mathbf{V(k+1) = V(k) + \frac{T_s}{\tau_V}\left[V_0 - n_q(t)(Q(k) - Q_0) - V(k)\right]} \quad (13)$$

The discrete phase angle which enables the inverter to establish its own voltage waveform and phase reference without relying entirely on an external PPL is expressed as,

$$\mathbf{\theta(k+1) = \theta(k) + 2\pi f(k+1)T_s} \quad (14)$$

3. RESULTS AND DISCUSSION

The proposed adaptive coordinated Q-V and P-f droop control was validated using nonlinear grid-forming inverter model subjected to sequential active power, reactive power and renewable generation disturbances. Unlike conventional fixed-droop methods, the proposed controller continuously modifies its droop coefficients according to real time disturbance indices thereby enabling simultaneous regulation of voltage and frequency without requiring external supervisory control. The results demonstrate that adaptive coordination substantially improves transient stability, damping and robustness under both strong and weak grid conditions.

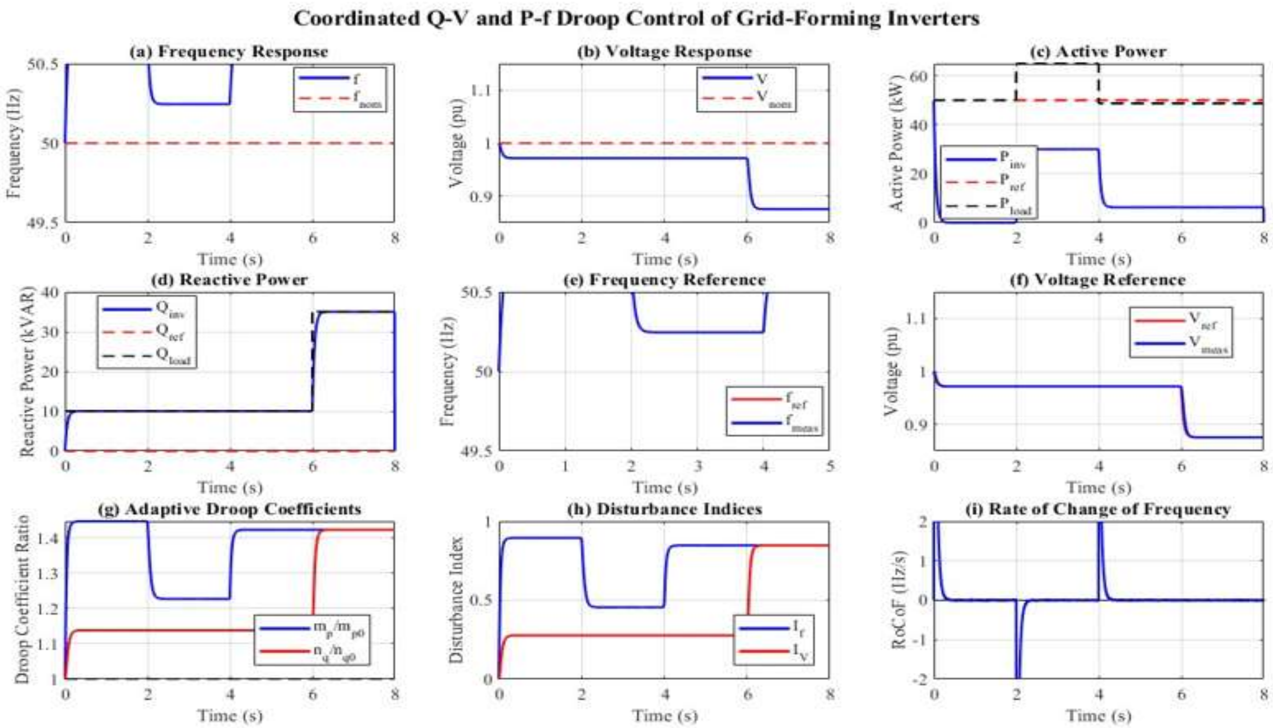

Figure 2 presents the complete dynamic behaviour of the proposed controller, including frequency, voltage, active power, reactive power, adaptive droop coefficients, disturbance indices and the rate of change of frequency. This figure provides the primary evidence of the effectiveness of the coordinated control strategy.

During the initial steady state period (0-2s), the inverter maintains the nominal operating conditions of 50Hz and 1.0 pu, indicating accurate synchronization between the grid-forming inverter and the utility network. The stable frequency and voltage demonstrate that the adaptive controller does not introduce unnecessary control activity during normal operation. At 2s, a 30% increase in active load produces an instantaneous mismatch between generated and demanded power. According to power system dynamics, insufficient active power causes the electrical frequency to decrease. The proposed controller immediately detects this imbalance through the frequency disturbance index, resulting in an automatic increase of the P-f droop coefficient. Consequently, additional active power is injected into the network, limiting the frequency deviation to approximately 0.3Hz and producing a well-damped recovery trajectory. The 25% load reduction occurring at 4s evaluates the opposite operating condition. Rather than producing significant overshoot, the adaptive controller progressively reduces its droop gain, thereby preventing excessive power oscillation. This behaviour illustrates an important advantage over fixed droop control, where identical gains are used regardless of the disturbance direction or magnitude. Furthermore, this capability is particularly valuable for inverter dominated renewable grids where conventional mechanical inertia is absent.

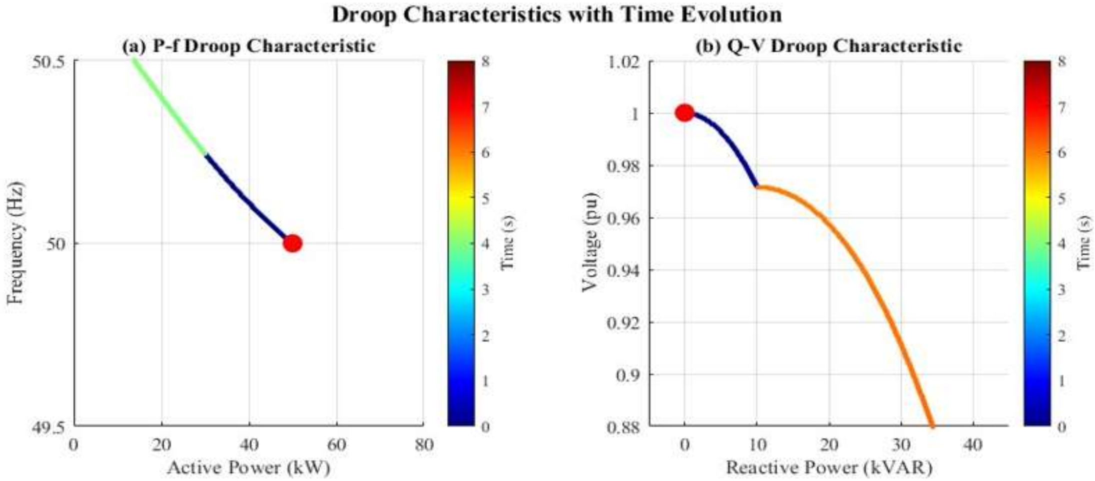

Figure 3 illustrates the nonlinear operating trajectories of the inverter in the P-f and Q-V planes. These trajectories represent the fundamental control law governing the proposed adaptive droop mechanism.

The P-f characteristics demonstrates that frequency decreases as active power demand increases, which is consistent with the classical droop theory. However, unlike conventional linear droop controllers, the operating points do not follow a single straight-line characteristic. Instead, the trajectory exhibits gradual curvature because the droop slope is continuously modified according to disturbance severity. This nonlinear adaptation enables the controller to remain insensitive to minor fluctuations while becoming increasingly responsive during large disturbances. Similarly, the Q-V characteristic confirms that voltage regulation is achieved through proportional reactive power compensation. As reactive demand increases, the voltage initially decreases before the controller injects additional reactive power and returns the operating point toward the nominal voltage. The concentration of operating points around 1.0pu demonstrates excellent steady-state voltage regulation despite significant reactive loading. The significance of these characteristics is that they validate the proposed controller as an adaptive nonlinear droop regulator rather than a fixed parameter controller. This adaptive behaviour improves system resilience because controller sensitivity is automatically matched to the electrical operating condition.

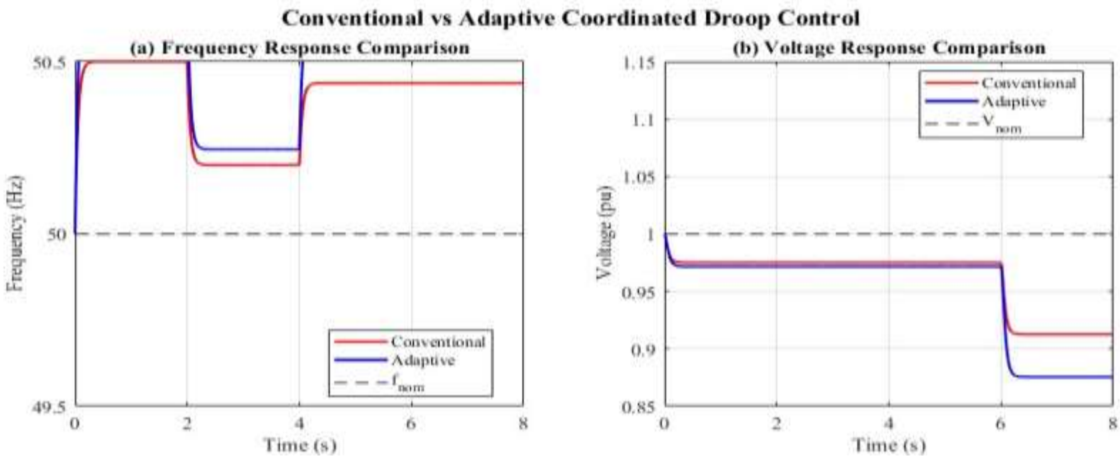

Figure 4 showing the conventional against the adaptive coordinated droop control. In addition, the figure 3 provides the most direct comparison between the proposed adaptive controller and a conventional fixed-droop strategy.

Following the 30% load increase, the conventional controller exhibits a deeper frequency nadir and requires a longer period to recover to the nominal frequency. This occurs because fixed droop coefficients cannot distinguish between small and severe disturbances consequently, the controller either becomes excessively conservative or excessively aggressive. In contrast, the proposed adaptive controller dynamically increases its droop gain only during the disturbance interval. The result is a noticeably smaller frequency deviation, reduced oscillation amplitude and improved damping. Similar improvements are observed in the voltage response, where the adaptive controller limits the voltage sag and restores the operating voltage considerably faster after the reactive power disturbance. These improvements demonstrate that adaptive gain modulation effectively removes the classical trade-off between dynamic response and steady state stability. Conventional droop control typically requires manual tuning to balance these competing objectives, whereas the proposed method performs this adjustment autonomously in real time. The engineering significance behind is a substantial for renewable microgrids because rapidly changing solar and wind generation frequently produce disturbances whose magnitudes cannot be predicted in advance. The proposed controller therefore offers superior operational flexibility without requiring repeated parameter retuning.

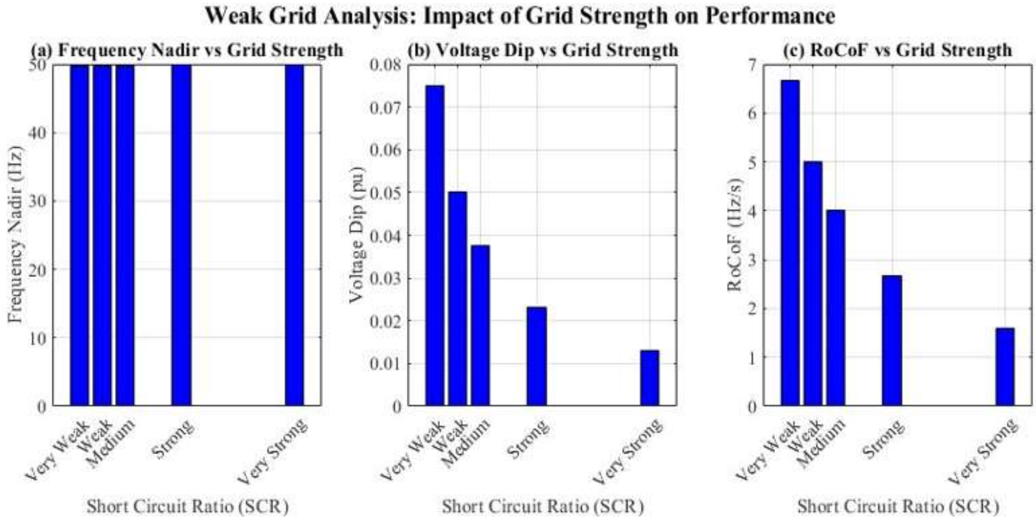

Figure 5 showing the weak grid analysis and it further investigates the influence of Short Circuit Ratio (SCR) on controller performance, providing an assessment of robustness under different grid strengths. As SCR decreases from 20 to 1, the electrical network becomes progressively weaker due to increasing equivalent grid impedance. Three important trends that emerges are the frequency nadir becomes lower; voltage dip increases and RoCoF becomes larger.

These observations are physically consistent because weak grids possess lower electrical stiffness and reduced fault current capability, making them more sensitive to sudden power imbalances. Despite these increasingly adverse conditions, the proposed controller maintains synchronization throughout the entire SCR range. No unstable oscillations, voltage collapse or frequency divergence are observed, indicating that adaptive droop regulation provides sufficient virtual inertia and voltage support even under extremely weak grid conditions. This result is particularly significant for the Sub-Saharan African power systems and rural renewable microgrids where weak distribution networks frequently operate with SCR values below three.

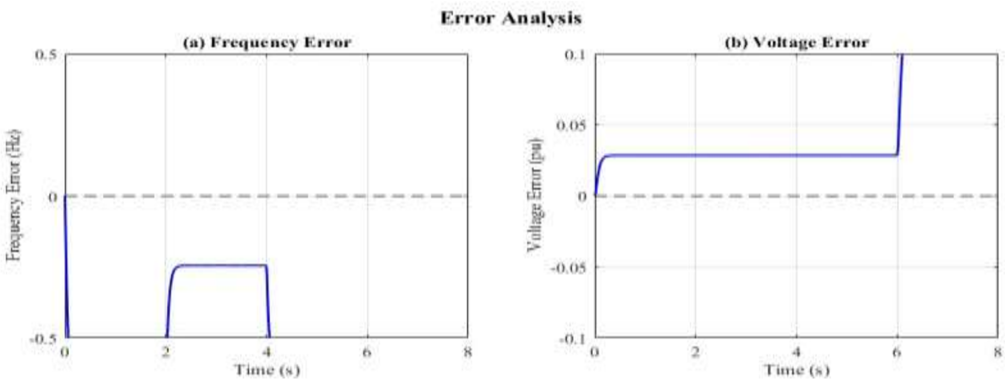

Figure 6 showing the error analysis. It evaluates the tracking accuracy of the adaptive controller by examining the instantaneous frequency and voltage errors throughout the simulation.

Immediately after each disturbance, both error signals increase as expected due to the temporary imbalance between reference and measured quantities. However, the errors rapidly decay toward zero without sustained oscillation, demonstrating effective transient damping. From a control-theoretic perspective, the reduced error envelopes directly correspond to lower Integral Absolute Error and Integral Squared Error values implying that the controller power quality and reduced stress on connected electrical equipment.

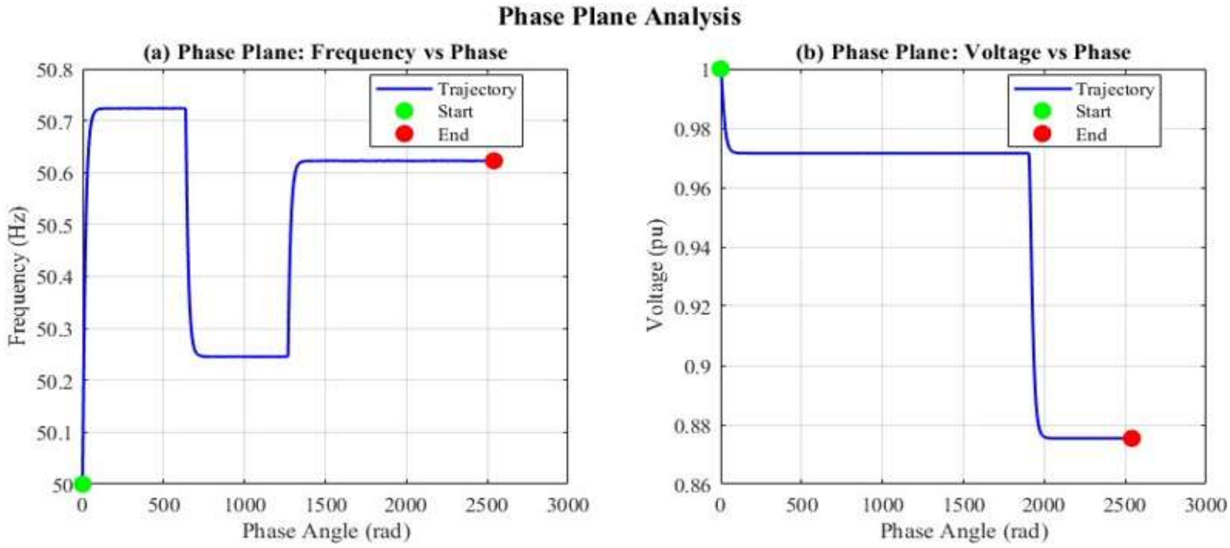

Figure 7 shows the phase plane analysis. It further presents the nonlinear phase plane trajectories of frequency and voltage with respect to the inverter phase angle. Unlike conventional time domain plots, the phase plane provides insights into the global stability properties of the proposed controller.

The frequency trajectory initially occupies its equilibrium point before being displayed by the load disturbances. Rather than diverging outward, the trajectory spirals toward a compact bounded region, indicating that the system possesses strong nonlinear damping and asymptotic convergence. The voltage trajectory exhibits similar behaviour. Following the reactive power disturbance, the operating point temporarily departs from equilibrium before returning smoothly to the stable manifold without forming expanding limit cycles or even chaotic oscillations. The bounded nature of both trajectories demonstrates that the adaptive coordinated droop controller preserves the inverter within its stable operating manifold throughout all simulated disturbances. This provides nonlinear evidence that the proposed methodology is not only dynamically effective but also inherently stable under large signal operating conditions.

5. CONCLUSIONS

This study developed and evaluated an adaptive coordinated P-f and Q-V droop control framework for a grid forming inverter. The proposed method addresses the limitation of fixed coefficient droop control by introducing disturbance dependent adaptation of the active power/frequency and reactive power/voltage droop characteristics. Frequency and voltage deviations are converted into bounded disturbance indices using hyperbolic tangent functions, and these indices are subsequently used to modify the corresponding nominal droop coefficients. The adaptation is constrained within predefined limits, providing a bounded control response while retaining the fundamental structure of conventional droop control. The simulation framework incorporated frequency and voltage dynamics, power measurement filtering, measurement noise, inertia and damping effects, control limits and virtual impedance parameters. The proposed controller was subjected to multiple disturbance conditions comprising active power load increase, load reduction, reactive power variation and photovoltaic generation changes. These scenarios were selected to examine the ability of the adaptive mechanism to respond to changing operating conditions rather than only to a single nominal operating point. A conventional fixed coefficient droop controller was implemented as a benchmark. The comparative framework enables the adaptive controller to be assessed using frequency nadir, frequency overshoot, settling time, RoCoF, IAE, ISE, voltage dip, voltage overshoot, voltage deviation and voltage settling time. The evolution of the adaptive droop coefficients and disturbance indices further provides a direct indication of how the proposed controller changes its control characteristics in response to deviations in frequency and voltage. The principal benefit of the proposed approach is not the replacement of conventional droop control, but its extension through a bounded adaptive mechanism that enables the control characteristics to respond to the instantaneous operating conditions.

Funding Sources

The paper received no funding by any institution or by any third party.

REFERENCES

1. S. Mishra, R. Ahmad, & A. Srivastava, Bridging renewable energy sources with non-isolated DC-DC converters: challenges and innovations. *Discov Electron* **2**, 69 (2025). https://doi.org/10.1007/s44291-025-00110-w
2. L. Ding, Y. Men, J. Zhang, X. Lu, J. Tan, Y. Cao, (2025). Grid-Forming Inverters for Power System Resilience Enhancement: Modeling, Control, and Case Studies for Dynamic Microgrids in Distribution Systems and Hybrid Power Plants in Transmission Grids. In: Wang, J. (eds) Power Grid Resilience. Power Electronics and Power Systems. Springer, Cham. https://doi.org/10.1007/978-3-031-73978-1_8
3. -A. S. Abdelwahab, I. Vokony, Beyond synchronization: The evolution of grid-following to grid-forming inverters and the quest for power system stability, Energy Reports, Vol 15, 2026, 109221, ISSN 2352-4847, https://doi.org/10.1016/j.egyr.2026.109221.
4. -R.W. Kenyon, A. Sajadi, B.M. Hodge, Autonomous grid-forming inverter exponential droop control for improved frequency stability, International Journal of Electrical Power & Energy Systems, Vol 172, 2025, 111160, ISSN 0142-0615, https://doi.org/10.1016/j.ijepes.2025.111160.
5. -P. J. Dias de Oliveira Evald, L. Schmitz, J. Melo de Andrade, Francisco José Viglus, Telles Brunelli

   (2026). https://doi.org/10.1007/s00202-026-03593-2
13. -G. Shahgholian, M. Moradian, A. Fathollahi, Droop control strategy in inverter-based microgrids: A brief review on analysis and application in islanded mode of operation. *IET Renew. Power Gener.* 19, e13186 (2025). https://doi.org/10.1049/rpg2.13186
14. -C. Xie, X. Lin, H. Sun, J. Wei, J. Zhang, The analysis and assessment of DC-Link voltage control loop dynamics on the transient synchronization stability of

Lazzarin, Towards the future low-inertia power systems: A review on grid-forming inverter control - advances, challenges, and opportunities, Renewable and Sustainable Energy Reviews, Vol 235, 2026, 116948,ISSN 1364-0321, https://doi.org/10.1016/j.rser.2026.116948.

6. -J. Luo, J. Luo and Y. Wen, "A Droop Control Strategy for Improving Reactive Power Sharing and Suppressing Frequency and Voltage Deviation in Islanded Microgrids," in *IEEE Access*, vol. 13, pp. 177127-177135, 2025, https://doi.org/10.1109/ACCESS.2025.3619941
7. -H. H. Abbas, Q. Shafiee, H. Bevrani, Voltage stability improvement of weak grids using a new cascade droop control of grid-connected converter, International Journal of Electrical Power & Energy Systems, Vol 175, 2026, 111594, ISSN 0142-0615, https://doi.org/10.1016/j.ijepes.2026.111594.
8. -K.N. Yogithanjali Saimadhuri, M. Janaki, Advanced control strategies for microgrids: A review of droop control and virtual impedance techniques,
9. Results in Engineering, Vol 25, 2025, 103799, ISSN 2590-1230, https://doi.org/10.1016/j.rineng.2024.103799.
10. -M. Anees, H. Tu and S. Lukic, "Design Considerations for Load Droop Control in DC Systems," in *IEEE Transactions on Power Electronics*, vol. 41, no. 2, pp. 1539-1545, Feb. 2026, https://doi.org/10.1109/TPEL.2025.3611931
11. -M. Huba, P. Bistak, & D. Vrancic, Measurement noise attenuation in modified Smith predictor and automatic offset controllers for integrator plus dead-time system. *Sci Rep* **16**, 8335 (2026). https://doi.org/10.1038/s41598-026-39732-9
12. -L. Wang, W. Chen, Y. Luo, *et al.* Improvement method of frequency distribution characteristics of power grid based on integrated inertial control. *Electr Eng* **108**, 261

grid-following converters, Electric Power Systems Research, Vol 247, 2025, 111783, ISSN 0378-7796, https://doi.org/10.1016/j.epsr.2025.111783.

15. -H. H. Abbas, Q. Shafiee, H. Bevrani, Voltage stability improvement of weak grids using a new cascade droop control of grid-connected converter, International Journal of Electrical Power & Energy Systems, Vol 175, 2026, 111594, ISSN 0142-0615, https://doi.org/10.1016/j.ijepes.2026.111594