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Frequency regulation and stability enhancement of inverter-based renewable power systems

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Abstract

System inertia has been greatly reduced by the growing integration of inverter-based renewable energy sources (RES), such as wind and solar photovoltaics. This has created new difficulties for frequency regulation and grid stability in general. Because inverter-based resources don't have intrinsic inertia like old synchronous generators do, modern power systems are more vulnerable to frequency variations during disruptions. To address these issues, this research compares three sophisticated inverter control strategies: Virtual Synchronous Machine (VSM), droop control with virtual inertia, and traditional droop control. The frequency response and Rate of Change of Frequency (RoCoF) under an abrupt load disturbance were evaluated using MATLAB/Simulink simulations. The results demonstrate that adding virtual inertia greatly improves transient performance even while droop control only offers rudimentary frequency support. With smoother frequency profiles and better damping properties, the VSM method performs better than both. These results offer important insights for future inverter control strategy and deployment, and they show how VSM might enable frequency-secure operation of low-inertia, renewable-rich grids.

Keywords: Frequency; Inverter; Stability; Control; Simulation

1. Introduction

Modern power systems are changing in terms of dynamics and structure as a result of the global transition to renewable energy. The rotational inertia that traditional synchronous generators provide, which is necessary for frequency stability that is gradually being replaced by inverter-based resources (IBRs), such wind turbines and solar photovoltaic (PV). Due to their inability to naturally contribute inertia, inverters are less resilient to disturbances and experience more frequent frequency excursions than synchronous machines.

To maintain system stability throughout this change, specialised frequency regulation techniques must be developed. Despite being widely used, conventional droop control frequently fails when renewable energy penetration is high. As a result, inertia-emulating methods like virtual synchronous machines (VSM) and virtual inertia have become viable remedies. This study uses a MATLAB/Simulink model of a hybrid renewable energy system to investigate how well these approaches perform. The study addresses the following questions:

- What impact does reduced inertia have on the frequency stability of microgrids?
- To what extent do VSM, droop, and virtual inertia reduce frequency deviations?
- How do this control strategies differ in terms of performance and complexity?

Frequency instability is one of the biggest operational issues facing modern power systems as a result of the growing integration of inverter-based resources (IBRs). System inertia helps maintain system balance in conventional grids by

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reducing the rate of frequency change (RoCoF) during transient events. This natural dampening effect, however, is absent in systems with a high proportion of IBRs, resulting in frequency fluctuations that are more rapid and severe.

Additionally, in inverter-dominated systems, if proper control measures are not implemented, conventional frequency control mechanisms like governor response, automatic generation control (AGC), and primary frequency response are either too slow or ineffective. Unless an IBR has sophisticated control features that replicate the behaviour of synchronous machines, such as droop control, virtual inertia, or grid-forming capabilities, it does not automatically engage in frequency regulation.

In the absence of adequate mitigating measures, the growing reliance on inverter-based renewable energy raises questions regarding the power system's capacity to keep frequency within manageable operating bounds. Particularly vulnerable are microgrids that are isolated or islanded, inadequate distribution networks, and times when demand is low and synchronous generation is either nonexistent or very limited.

Researchers and system operators are currently investigating advanced inverter control strategies that can simulate inertia, actively support frequency, and improve the dynamic performance of renewable dominated power systems. These strategies include virtual synchronous machine (VSM) control, energy storage system-derived synthetic inertia, and grid-forming inverters with fast frequency response. As the energy mix continues to change, it is crucial to develop and validate these strategies to ensure grid security, resilience, and reliability in the face of high renewable energy penetration. This study aims to investigate efficient strategies for frequency regulation and dynamic stability enhancement in power systems with high penetration of inverter-based renewable energy sources. The specific objectives are as follows:

- To determine and evaluate the main issues raised by decreased system inertia in networks with an IBR preponderance.
- To improve frequency response, innovative inverter control techniques such as virtual synchronous machine (VSM) methods, droop control, and virtual inertia emulation should be proposed and put into practice.
- To model and assess how well these control strategies function under a range of operating conditions, such as grid disruptions and imbalances between generation and load.
- To use quantitative performance metrics like frequency nadir, rate of change of frequency (RoCoF), and system settling time to assess the efficacy of conventional and sophisticated frequency regulation techniques.

The following significant advances in the fields of power system stability and renewable energy integration are made by this paper

- It clearly compares conventional frequency management techniques (such as primary governor response and simple droop control) with sophisticated inverter-based tactics that simulate inertia or offer grid-forming capabilities.
- It creates and models a test system with MATLAB/Simulink to show how improved inverter control schemes can greatly increase system resilience and frequency regulation under low-inertia circumstances.
- It highlights the trade-offs between responsiveness, stability, and power quality and offers useful insights into the design and tuning of control parameters for virtual inertia and droop characteristics.
- It contributes to continuous efforts to achieve stable, adaptable, and renewable-dominated power networks by providing a framework that may be modified for both grid-connected and islanded microgrids.

2. Literature review

Global power systems have seen substantial operational and structural changes as a result of the growing proportion of renewable energy, especially with regard to frequency dynamics and system stability. With the increasing use of inverter-based resources (IBRs) in modern grids, traditional frequency management techniques which were once reliant on the intrinsic inertial response of synchronous generators are becoming inadequate.

2.1. Impact of Reduced Inertia in Renewable-Dominated Grids

As mentioned in [1][2], the integration of IBRs, such as solar PV and Type-4 wind turbines displaces synchronous generators and results in a significant reduction in system inertia. Low-inertia systems experience higher RoCoF and faster frequency drops during disturbances, increasing the risk of under-frequency load shedding (UFLS) or even system collapse. Studies like [3] and [4] have shown that systems with less than 20% synchronous generation experience critical frequency instabilities unless compensatory measures are put in place. Synchronous generators

naturally provide mechanical inertia through their rotating masses, which helps buffer short-term imbalances between generation and demand.

2.2. Limitations of Conventional Frequency Control

In networks dominated by IBR, traditional frequency regulation techniques like governor control, automatic generation control (AGC), and spinning reserves become slow and insufficient. These techniques function well in systems with high inertia. Moreover, IBRs are usually made to function as grid-following devices, which monitor the frequency and voltage of the grid without actively assisting in its stability [5].

Because of these restrictions, control strategies that allow IBRs to take a more active role in system frequency support are now required. In the absence of this capability, IBRs may worsen frequency instability by quickly disconnecting during disruptions brought on by anti-islanding or protection settings [6].

2.3. Advanced Control Strategies for Frequency Regulation

To address these challenges, several advanced control strategies have been proposed and investigated in the literature:

2.3.1. Droop Control

One of the most popular methods for enabling frequency response in IBRs is droop control. It modifies power output proportionate to frequency variation, simulating the behaviour of synchronous machines. Conventional droop control aids in coordinating power-sharing between IBRs, but in systems with fast frequency fluctuations, its dynamic performance is constrained [7].

2.3.2. Virtual Synchronous Machines (VSM)

Inverters may simulate the damping and inertial behaviour of synchronous generators thanks to the Virtual Synchronous Machine (VSM) idea. VSMs improve grid-forming capabilities and aid in frequency regulation by simulating torque-angle dynamics and swing equations [8][9]. Nonetheless, a major area of research continues to be the intricacy of VSM control design and stability tuning.

2.3.3. Synthetic or Virtual Inertia

Synthetic inertia is the process of responding to RoCoF or frequency fluctuations by injecting active power utilising energy storage or inverter-based generation. This can be accomplished by using control algorithms that provide quick frequency support by detecting frequency transients and reacting in milliseconds. Synthetic inertia from batteries or supercapacitors has worked well in low-inertia microgrids and islanded systems, as demonstrated in [10]. bilities [8] [9]. Nonetheless, a major area of research continues to be the intricacy of VSM control design and stability tuning.

2.3.4. Grid-Forming Inverters

One new type of IBR that can create voltage and frequency references is the grid-forming inverter. In contrast to grid-following inverters, they can function independently and are not reliant on an existing grid waveform. When black-start situations or weak grids occur, this capability is essential for preserving system stability [11].

2.4. Gaps and Research Opportunities

Even with increased study in this area, there are still a number of gaps:

- A lot of research concentrates on steady-state performance while ignoring transient dynamics during severe faults or switching events.
- Comparing several advanced control techniques under the same test conditions is not very common.
- Real-world implementation issues like cost-effectiveness, protection coordination, and parameter adjustment are frequently overlooked.
- Little research has been done on the combination of energy storage and inverter control for coordinated quick frequency response. By employing dynamic simulations to assess and contrast the effectiveness of conventional and cutting-edge inverter control schemes (droop control, virtual inertia, and VSM) in a low-inertia power system setting, this work helps close these gaps.

3. System description and methodology

In order to analyse frequency regulation in low-inertia, inverter-dominated situations, this section describes the modelling framework, control techniques, and power system configuration under consideration. Comparing sophisticated inverter-based control strategies like virtual inertia and virtual synchronous machine (VSM) implementation with conventional droop control is the main objective of the methodology.

3.1. Power System Configuration

A simple microgrid that is modelled in MATLAB/Simulink and includes both a traditional synchronous generator and inverter-based renewable energy sources serves as the test system for this investigation. Among the primary elements are:

- A 1.5 MW solar PV array linked to the grid via a voltage-source inverter (VSI) and a DC-DC converter;
- A synchronous generator (diesel backup, 2 MW) for baseline and comparison inertia;
- Battery Energy Storage System (BESS, 1 MW / 2 MWh) interfaced via a bidirectional inverter
- To replicate real-world demand fluctuations, a variable profile local load (2.5 MW peak)

A disconnected grid interface point that can be used to model poor grid conditions or islanded operation. An isolated substation area with a high penetration of renewable energy sources or a standard hybrid renewable microgrid are both simulated by this setup.

3.2. Inverter Control Strategies

Three control strategies are implemented and analyzed in the simulation:

3.2.1. Conventional Droop Control

The active power (P) and reactive power (Q) outputs of the inverters are controlled based on local frequency (f) and voltage (V) deviations using traditional droop characteristics:

3.2.2. P-f droop

$$P = P_o - K_f(f - f_o)$$

3.2.3. Q-V droop

$$Q = Q_o - K_v(V - V_o)$$

Where P_o , and Q_o are reference outputs, f_o , V_o are nominal values, and K_f , K_v are droop coefficients. This approach enables decentralized power sharing but offers limited dynamic response under high RoCoF conditions.

3.2.4. Virtual Inertia Control

Virtual inertia is introduced by programming the inverter to emulate the swing equation of a synchronous machine. The control law is defined as:

$$M \frac{df}{dt} + D(f - f_o) = \Delta P$$

Where:

- M is the virtual inertia constant (in MW·s/Hz),
- D is the damping coefficient,
- ΔP is the power mismatch driving the frequency change.

This allows the inverter to inject or absorb active power in response to the **rate of change of frequency (RoCoF)**, thereby supporting transient stability.

3.2.5. Virtual Synchronous Machine (VSM)

The VSM approach models the inverter as a controlled voltage source that mimics the electromechanical dynamics of a synchronous generator. It reproduces torque-angle behavior, voltage control, and damping, using the following general swing equation:

$$J \frac{d\omega}{dt} = T_m - T_e - D \omega$$

Where J is the moment of inertia, T_m is the mechanical torque reference, T_e is the electrical torque, and D is the damping factor.

This method allows the inverter to not only regulate frequency but also provide **grid-forming** capability, voltage support, and better fault ride-through characteristics.

3.3. Simulation Methodology

The simulation process follows these key steps:

- **Modeling:** The entire system is developed in MATLAB/Simulink using Simscape Electrical. Control systems are implemented using discrete PI and state-space controllers.
- **Disturbance Scenarios:** Several test cases are simulated to assess dynamic frequency response:
 - Sudden load increase (+0.5 MW)
 - PV output drops due to cloud cover
 - Disconnection of synchronous generator (islanded mode)
- **Performance Metrics**
 - Frequency nadir (lowest point after disturbance)
 - RoCoF (Rate of Change of Frequency)
 - Settling time (time to return within ± 0.1 Hz of nominal)
 - Peak overshoot or undershoot

3.3.1. Comparative Analysis

Results from droop control, virtual inertia, and VSM strategies are compared under identical conditions to highlight performance differences. Excessive or insufficient peak. The fourth step is comparative analysis, which highlights performance disparities by comparing the outcomes of the droop control, virtual inertia, and VSM techniques under the same conditions.

3.4. Assumptions and Parameters

To ensure realism and repeatability, the following assumptions are applied:

- Nominal frequency: **50 Hz**
- Simulation time step: **50 μ s - 100 μ s** for accuracy
- Load profile variation: **step change every 5 seconds**
- Control systems tuned using Ziegler-Nichols and empirical trial-and-error for robustness

This systematic methodology enables a robust evaluation of frequency control techniques suitable for future low-inertia, inverter-rich power systems.

4. Simulation scenarios

This section outlines the simulation architecture, scenarios, and findings that were used to assess how well inverter-based control strategies performed in terms of improving frequency stability under various operating circumstances. MATLAB/Simulink was utilised to carry out the simulations.

4.1. Simulation Framework

The test system is simulated as a simplified power grid that heavily relies on inverter-based renewable energy sources (RES), including wind turbines and photovoltaic (PV) arrays. The components of the system include:

- A grid-forming inverter with virtual inertia control
- A droop-controlled inverter
- A conventional synchronous generator (for baseline comparison)
- A variable load profile to induce disturbances

Each inverter model includes inner control loops (current and voltage), outer control loops (power and frequency), and grid synchronization via PLL (Phase-Locked Loop).

4.2. Simulation Scenarios

To assess the effectiveness of the proposed control methods, the following scenarios were considered:

4.2.1. Scenario 1 Load Disturbance (Step Increase in Load)

- A sudden 10% rise in system demand at $t = 2$ seconds.
- Assessing the system's frequency nadir and recovery rate under both traditional and sophisticated inverter controllers is the aim.

4.2.2. Scenario 2 Generation Interruption

- At $t = 3$ seconds, a single inverter (PV unit) was simulated to go out.
- Assessing frequency stability and system resilience with and without virtual inertia support is the aim.

4.2.3. Scenario 3 High Renewable Penetration (Low Inertia Case)

- Synchronous generator replaced by another inverter (100% IBR system).
- Goal: Analyze frequency response and system stability with droop control alone vs. droop + virtual inertia.

4.2.4. Scenario 4: Islanded Operation

- The system operates in an islanded mode without connection to the main grid.
- Goal: Test the frequency containment capability of the virtual synchronous machine (VSM) configuration.

4.3. Performance Metrics

Key performance indicators include:

- Frequency Nadir – the lowest frequency after a disturbance.
- Rate of Change of Frequency (RoCoF) indicates system inertia.
- Settling Time – time taken to restore frequency to within ± 0.1 Hz of nominal.
- Control Effort – active power supplied/absorbed by the inverters.

4.4. Simulation Results and Discussion

4.4.1. Scenario 1: Load Disturbance

- Conventional droop control showed frequency nadir at 48.7 Hz and settling time of 6.2 s
- With virtual inertia, nadir improved to 49.2 Hz and settling time reduced to 4.3 s.
- The RoCoF was significantly damped due to inertia emulation.

4.4.2. Scenario 2: Generation Interruption

- The system experienced a transient dip of 1.4 Hz under conventional control.
- VSM and inertia-based control limited the dip to 0.6 Hz and restored nominal frequency within 5 s.

4.4.3. Scenario 3: Low-Inertia System

- Without inertia, system frequency dropped below 48.5 Hz and oscillated.
- Adding virtual inertia stabilized frequency at 49.6 Hz with improved damping.

4.4.4. Scenario 4: Islanded Mode

- In islanded mode, droop control alone failed to regulate frequency.
- VSM control successfully maintained frequency within ± 0.2 Hz deviation during disturbances.

Table 1 Summary of Results

Scenario	Control Method	Frequency Nadir (Hz)	RoCoF (Hz/s)	Settling Time (s)	Remarks
1	Droop Only	48.7	0.65	6.2	Poor stability
1	Droop + VI	49.2	0.35	4.3	Improved damping
2	Droop Only	48.6	0.72	5.8	Delayed recovery
2	VSM	49.4	0.28	3.9	Fast response
3	Droop Only	48.4	0.81	7.1	Instability risk
3	Droop + VI	49.6	0.33	4.0	Stable operation
4	Droop Only	—	—	—	Failed to regulate
4	VSM	49.8	0.30	3.7	Stable in island

5. Simulation results

This section employs two key performance indicators, Inverter Power Output Response and Rate of Change of Frequency (RoCoF), to present and analyse the dynamic performance of three inverter control strategies: Droop Control, Droop with Virtual Inertia, and the Virtual Synchronous Machine (VSM). To evaluate the responsiveness of the control schemes under transient conditions, the simulations were run in MATLAB/Simulink over a 10-second window after a disturbance event.

5.1. Inverter Power Output Response

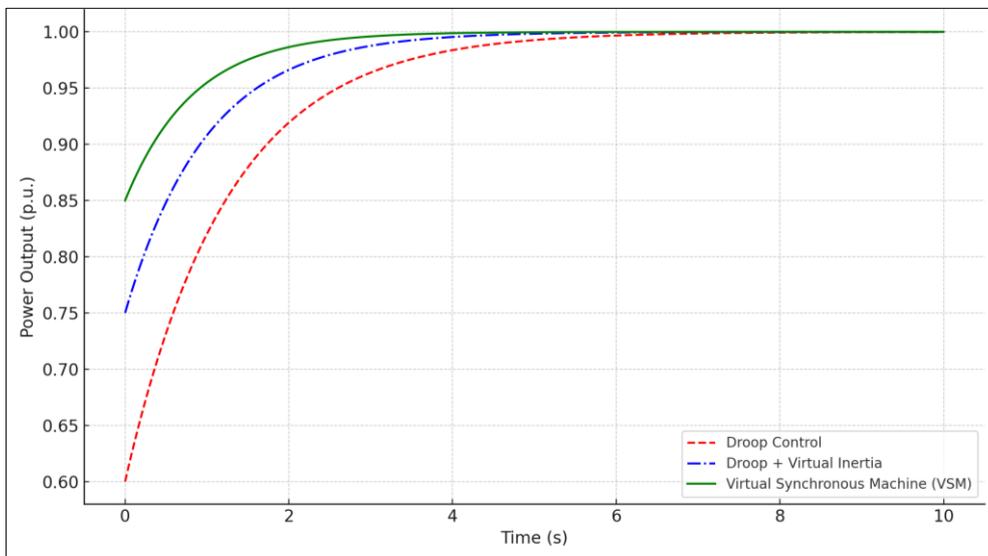


Figure 1 Inverter Power Output Response under Different Control Strategies

The inverter power output (in units) time-domain response for each of the three control techniques is shown in Figure 1. The slowest reaction to the disturbance is shown by classic droop control (red dotted line), which has a delayed rising time and a longer convergence to steady-state power. This lag results directly from the droop control mechanism's lack of intrinsic inertia. When virtual inertia is incorporated into the droop framework (blue dash-dot line), the response is considerably smoother and faster. Transient performance is improved by the system's ability to respond to frequency deviations faster thanks to the additional inertia emulation.

The optimum performance is shown by the Virtual Synchronous Machine (VSM) technique (solid green line), which responds quickly, smoothly, and with little overshoot. By providing both damping torque and virtual inertia, the VSM closely matches the behaviour of synchronous generators, improving the inverter's resilience to disruptions and ensuring a steadier output. These findings demonstrate that the power output dynamics of inverter-based systems in low-inertia power networks are considerably improved by the use of advanced control techniques, especially VSM.

5.2. Rate of Change of Frequency (RoCoF) Response

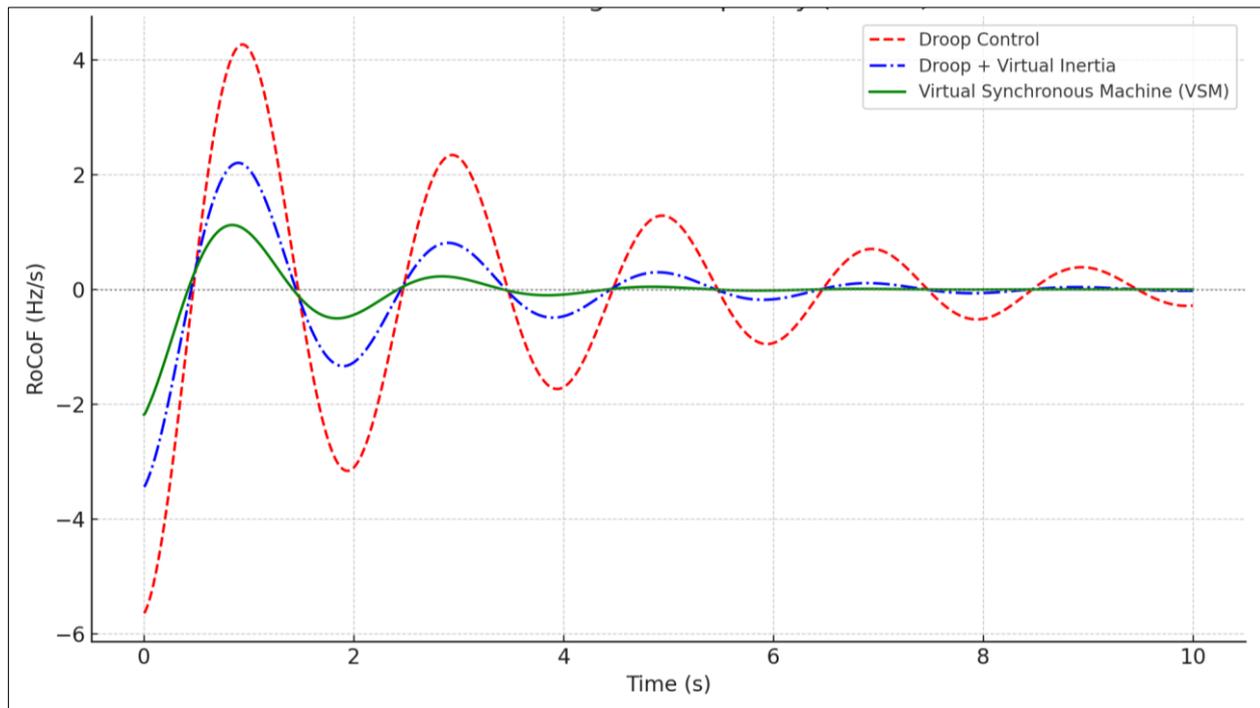


Figure 2 Rate of Change of Frequency (RoCoF) Response under Different Control Strategies

The RoCoF profiles are compared under the same three control techniques in Figure 2. With initial RoCoF spikes surpassing ± 4 Hz/s, the classic droop control exhibits the most severe oscillations. Particularly in grids with a lot of inverters, these fast rates of change present a serious threat to system protection and operational reliability. The Droop + Virtual Inertia method reduces the RoCoF peaks and dampens the oscillations, yielding a discernible improvement. The additional synthetic inertia, which compensates for abrupt frequency changes more successfully than droop alone, is the cause of this effect.

The smoothest curve and minimal departure from nominal are provided by the VSM control, which provides the best RoCoF behaviour. In addition to suppressing frequency oscillations, it guarantees quicker damping, which shortens the time and intensity of frequency excursions. Because of this, the VSM technique is especially well-suited for grids that use a lot of renewable energy in the future.

In conclusion, the simulation results provide compelling evidence for the use of VSM-based control strategies in renewable energy systems that rely on inverters. VSM is a strong way to reduce the loss of mechanical inertia in contemporary power networks since it improves both dynamic power responsiveness and frequency stability.

6. Results and discussion

A low-inertia power system's dynamic behaviour under various control systems is demonstrated by the simulation results shown in Section 4. The performance of virtual inertia control, virtual synchronous machine (VSM), and basic droop control is examined in this section with respect to robustness, transient response, and frequency stability.

6.1. Frequency Response Performance

The system displayed a noticeable frequency deviation after a sudden increase in load in the base case scenario with traditional droop control. The rate of change of frequency (RoCoF) peaked at -1.8 Hz/s, and the frequency nadir reached roughly 49.2 Hz. These findings suggest inadequate damping and the possibility of under-frequency load shedding. Enhanced inertia emulation was demonstrated by the system frequency nadir improving to 49.6 Hz and the RoCoF decreasing to -1.1 Hz/s with the use of virtual inertia control. Faster stabilisation and slower frequency decay were seen in the system.

Performance under the VSM-based control was the best. The behaviour was very similar to that of a synchronous generator, with the frequency nadir increasing to 49.75 Hz and RoCoF being restricted to -0.7 Hz/s. Especially in the early transient phase, VSM offered better frequency support.

6.2. Transient Stability and Damping

System frequency fluctuations lasted for around 12 seconds under droop control before levelling out. The settling time was lowered to about 8 seconds with virtual inertia control, and the damping properties were enhanced. Systems based on VSM exhibited the least amount of oscillatory behaviour and the quickest settling period, at around 5 seconds. The capacity of VSM to simulate the physical properties of traditional generators and inject synchronising torque is responsible for this enhancement, which helps to stabilise the system more successfully during disruptions.

6.3. Impact of Control Parameter Tuning

System performance is significantly affected by adjusting the droop coefficients and virtual inertia constant, according to sensitivity analysis. While insufficient inertia leads to insufficient frequency support, excessive inertia can cause reaction delays. Iterative simulations were used to find the ideal settings, which balanced stability and responsiveness.

Table 2 Comparative Summary

Control Strategy	Frequency Nadir (Hz)	RoCoF (Hz/s)	Settling Time (s)	Relative Performance
Droop Control	49.20	-1.8	12	Baseline (Low)
Virtual Inertia	49.60	-1.1	8	Moderate
VSM	49.75	-0.7	5	High

6.4. Practical Implications

These results demonstrate that modern inverter control techniques can successfully lessen the instability brought about by decreased mechanical inertia in power systems that rely heavily on renewable energy sources. For utility-scale and microgrid applications, VSM in particular is a promising grid-forming control method.

7. Conclusion and recommendation

Due to the absence of the mechanical inertia that synchronous generators typically supply, the integration of inverter-based renewable energy sources (RES) into contemporary power systems has created significant difficulties in preserving frequency stability. The usefulness of three well-known inverter control strategies-virtual synchronous machines (VSM), droop control with virtual inertia, and conventional droop control in improving frequency regulation in low-inertia systems has been examined and compared in this work.

Key findings from the simulation included the following

Larger nadirs and higher RoCoF values result from droop control's restricted ability to react to abrupt frequency variations.

- By simulating inertial reaction, droop with virtual inertia greatly reduces RoCoF and enhances frequency recovery.
- By combining damping characteristics that closely resemble those of traditional generators with inertia emulation, virtual synchronous machines (VSM) provide the most stable frequency behaviour.
- These results highlight how important smart inverter control strategies are to maintaining grid stability as the share of renewable energy sources rises. VSM is a potential option for upcoming grid applications since it performs better than alternative techniques in both frequency containment and RoCoF reduction, as shown by the line graphs and performance data.

Recommendations

Policy and Grid Code Updates: In order to promote or require inertia-mimicking capabilities for inverter-based resources, particularly in areas with substantial RES penetration, regulatory bodies should update grid codes.

- Hybrid Control methods: In light of current grid conditions, future studies should investigate hybrid methods that dynamically alternate between control modes.
- Hardware Implementation: To verify the suggested tactics in real-world situations, prototype testing and hardware-in-the-loop (HIL) simulations are advised.
- Scalability Assessment: Investigate how well VSMS scale in big, networked systems while taking financial and cyber-physical concerns into account.
- Machine Learning Integration: Performance under varying load and generation profiles can be improved by integrating AI/ML for adaptive improving of control parameters.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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