NIGERIAN JOURNAL OF ENGINEERING RESEARCH UNICROSS (NJERU)

Volume 2, Issue 1, 1st April, 2025

MITIGATING FREQUENCY IMPACTS OF RENEWABLE ENERGY SOURCES USING VIRTUAL INERTIA CONTROL FOR OPTIMAL POWER SYSTEM OPERATIONS

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Received: 2nd March, 2025 Reviewed: 14th March, 2025 Accepted: 30th March, 2025

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Abstract:

The increasing penetration of renewable energy sources (RES), such as wind and solar, has significantly reduced the conventional synchronous inertia in power systems, leading to frequency instability, higher Rate of Change of Frequency (RoCoF), and larger frequency deviations. This paper focuses on mitigating these frequency impacts using Virtual Inertia Control (VIC) for optimal power system operations. VIC was implemented and optimized using Particle Swarm Optimization (PSO) to enhance grid stability and ensure reliable system performance. This study investigates the effectiveness of VIC in improving frequency stability in high-RES penetration power systems. Through MATLAB/Simulink simulations, it was demonstrated that VIC significantly improves RoCoF and reduces frequency nadir following disturbances. The analysis of control strategies, including droop control and inertia emulation, revealed that proper tuning of virtual inertia parameters is crucial for optimal performance. The results confirmed that VIC enhances grid resilience, enabling smoother frequency regulation under varying renewable energy conditions. The simulations showed that increased RES penetration worsen frequency instability due to reduced system inertia. At 30% penetration, frequency deviations were moderate, while at 50% and 70% penetration, the system exhibited significant instability. VIC effectively mitigated these effects by providing synthetic inertia to compensate for the reduced natural inertia. Furthermore, PSO-based VIC tuning enhanced frequency stability beyond standard VIC implementations. The optimized VIC system achieved a lower RoCoF (-0.6 Hz/s compared to -0.8 Hz/s) and a faster settling time (4.44s compared to 5.71s), ensuring improved dynamic response and grid reliability. Overall, this study confirms that Virtual Inertia Control, particularly when optimized using PSO, is a powerful tool for mitigating frequency impacts in renewable energy-based power systems. The findings highlight VIC's crucial role in improving grid stability and ensuring the reliable operation of modern power networks with high renewable energy penetration.

Keywords: Frequency Stability, Inverter-Based Resources (IBRs), Particle Swarm Optimization, power systems, Rate of Change of Frequency, Renewable energy sources (RES), solar photovoltaic (PV), Virtual Inertia Control, wind turbines.

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I. INTRODUCTION

Driven by the urgency of climate change mitigation and sustainable development targets, nations worldwide are increasingly adopting renewable energy technologies such as wind and solar [1]. Inverter-based resources (IBRs) now represent a substantial portion of contemporary power systems. Unlike conventional synchronous machines that inherently contribute rotational inertia through their mechanical mass, renewable energy technologies interfaced via power electronics typically lack this crucial dynamic characteristic. Inertia serves a fundamental function in maintaining grid frequency stability by providing an immediate response to abrupt mismatches between generation and load. The replacement of traditional generators with renewable energy sources reduces system inertia, making power grids more susceptible to frequency instability [2,3]. Sudden changes in frequency, whether too low or too high, can lead to cascading system failures which will forced load reductions or complete blackouts. Maintaining frequency stability is essential for the dependable operation of a power system, as it helps keep the grid's frequency at its standard value (50 Hz or 60 Hz) despite variations in power generation or consumption. If not properly managed, frequency deviations can cause damage to electrical equipment, initiate cascading failures, and result in large-scale blackouts. Inertia, an inherent characteristic of rotating machines, plays a vital role in stabilizing the grid by providing essential damping during system disturbances. Power systems function based on the real-time equilibrium between electricity generation and consumption [4,5]. A sudden loss of generation or an unexpected increase in demand disrupts this balance, causing the system frequency to shift from its nominal value. Frequency stability is the grid's capacity to keep frequency variations within acceptable limits (usually ±0.5 Hz) during disturbances or sudden changes in supply and demand. Numerous electrical devices, including motors and transformers, are engineered to function optimally at designated frequencies. Sustained frequency deviations can lead to excessive heating, which may degrade component integrity and shorten their operational lifespan. Sudden declines in system frequency may activate automatic protection mechanisms, such as load shedding or generator tripping, which can escalate into widespread, unplanned power outages. In power systems, inertia is derived from the kinetic energy stored in rotating components like synchronous generators and turbines [6,7]. These components act to resist changes in their rotational speed, offering a quick response to fluctuations in power balance. When a disturbance happens, the resulting power shortfall leads to a frequency drop. Inertia helps mitigate this by releasing kinetic energy from the rotating masses, effectively "buying time" (ranging from seconds to minutes) for slower-acting control mechanisms to take effect [8]. This process is described by the swing equation, which links the rate of frequency change (RoCoF) to the system's inertia and the power imbalance. Greater system inertia leads to a lower Rate of Change of Frequency (RoCoF), which moderates the speed of frequency deviations and provides a critical window for implementing corrective actions such as primary frequency control through turbine governors or secondary control via automatic generation control (AGC). Conventional power systems primarily depend on synchronous generators such as those in coal, gas, and hydro plants which naturally supply inertia through their rotating masses. With the growing integration of inverter-based renewable sources like solar PV and wind, system inertia has declined, as these technologies lack physical rotation and therefore do not inherently contribute to inertial support. Virtual inertia control (VIC) offers a compelling approach by utilizing power electronic interfaces and energy storage technologies to replicate the inertial behavior that was once inherently delivered by conventional synchronous machines. Through real-time modulation of active power from inverter-based resources (IBRs) during frequency disturbances, virtual inertia control facilitates renewable energy contributions to frequency regulation, thus strengthening the stability of power systems with low inherent inertia [9].

The increasing adoption of renewable energy sources (RES) particularly wind and solar has introduced critical challenges in power system stability, especially in frequency regulation. Unlike traditional synchronous generators, RES-based generation units lack natural rotational inertia, leading to amplified frequency deviations during power imbalances. To address this issue, virtual inertia control (VIC) has emerged as a key solution, artificially replicating inertia to stabilize modern grids. This paper reviews existing VIC strategies, assesses their effectiveness in managing frequency fluctuations, and identifies unresolved research gaps. By evaluating control methodologies, optimization techniques, and implementation frameworks, this analysis provides a foundation for improving grid reliability through VIC while highlighting barriers to its widespread deployment. In the future power system with high-share of RESs, the overall inertia of the system would be significantly lower due to the incorporation of inverter-based RESs generation units, which are inertia-less. [10,11] discussed the high-share of inverter-based generation units and the resulting reduction in overall system inertia, could have significant impacts on the stability and operation of the power system.

To mitigate the impacts of low system inertia and improve the stability of low inertia power system, particularly the frequency stability, the emulation of additional inertia into the power system without using actual rotating mass in terms of virtual inertia becomes one of the promising solutions. [12,13] summarized several topologies to emulate the virtual inertia. All of these topologies are developed based on a similar basic concept. However, they differ in terms of the level of detail in their implementation. To give an insight on various topologies for virtual inertia emulation, several notable topologies where briefly discussed and the difference between the topologies where highlighted. [13] divided the virtual inertia emulation topology into three main categories. Such as Synchronous generator model-based topology, Swing equation-based topology, Frequency-power response-based topology. (a) Synchronous Generator Model-Based Topology: Synchronous generator model-based topology is the topology for virtual inertia emulation based on the full modeling of the dynamics of a synchronous generator (SG). One of the examples of topologies in this category is synchronverter. In synchronverter, both the electrical part (the interaction between windings) and the mechanical part of an SG (the rotating mass and inertia) are modeled. Hence, the dynamics of an SG could be accurately replicated. [14,15] carried out research works on the analysis and the improvement of synchronverter. (b) Swing Equation-Based Topology: Swing equation-based topology is the topology for virtual inertia emulation based on the swing equation of an SG. Hence, rather than full modeling of an SG, only the swing equation is modeled to emulate the virtual inertia. [16] introduced one of the well-known topologies in this category known as Ise Lab's topology. The topology works based on the measurement of grid frequency and the active power output of the inverter. Several research works on the analysis and the improvement of Ise Lab's topology are discussed by [17-19]. The other topology in this category is the synchronous power controller (SPC**).** (c) Frequency-Power Response-Based Topology: Frequency-power response-based topology is the topology for virtual inertia emulation based on the response to the frequency change. This topology uses the measurement of the derivative of the frequency change to emulate the virtual inertia. The virtual inertia emulation using the derivative of the frequency change has been discussed. One of the topologies in this category is the virtual synchronous generator (VSG). Research work on the implementation of VSG were discussed by [20]. In the frequency-droop control, a low pass filter employed in the measurement of its output power could be used to approximate the behavior of virtual inertia control. [21] analyzed the impact of high-penetration renewable energy injection on power system frequency stability, and derives the system frequency expressions in the absence of an FR scheme, and in the presence of droop/inertia/PD controls that are representative for various virtual synchronous generator-based FR schemes. Under the same constraint of available FR capacity, control parameter ranges of these FR schemes were obtained, and their optimal conditions for restraining the maxima of $\Delta\omega$ and RoCoF were identified and compared analytically. [22] explores state-of-the-art virtual inertia support strategies tailored to accommodate the increased penetration of RESs, it explores the existing virtual inertia techniques and control algorithms, parameters, configurations, key contributions, sources, controllers, and simulation platforms. The promising virtual inertia control strategies are categorized based on the techniques used in their control algorithms and their applications, it facilitate the current state of research paths concerning virtual inertia control techniques, along with the categorization and analysis of these approaches, and showcases a comprehensive understanding of the research domain, which is essential for the sustainable integration of renewable energy into modern power systems via power electronic interface. [23] reviewed the inertia concept and proposes a method to estimate the rotational inertia in different parts of the world. In addition, an extensive discussion on wind and photovoltaic power plants and their contribution to inertia and power system stability was presented. [24] provided a thorough understanding of the basic principles, synthesis, analysis, and control of virtual inertia systems. It uses the latest technical tools to mitigate power system stability and control problems under the presence of high distributed generators (DGs) and renewable energy sources (RESs) penetration. It uses a simple virtual inertia control structure based on the frequency response model, complemented with various control methods and algorithms to achieve an adaptive virtual inertia control respect to the frequency stability and control issues. This work captures the important aspects in virtual inertia synthesis and control with the objective of solving the stability and control problems regarding the changes of system inertia caused by the integration of DGs/RESs.

II. METHODOLOGY

The methodology is structured to ensure an effective approach to mitigating frequency impacts on renewable energy sources through virtual inertia control. The research follows a simulation-based experimental approach, where a power system model incorporating renewable energy sources is developed in MATLAB/Simulink. Virtual inertia control strategies are implemented using control system toolbox for designing and tuning the virtual inertia control system and tested to analyze their impact on system frequency stability. A test power system consisting of conventional generators, renewable energy sources, and an energy storage unit is modeled. The system is subjected to disturbances such as sudden load changes or generator tripping to evaluate frequency response characteristics. The virtual inertia control is integrated into the renewable energy system by continuously monitoring the system frequency using frequency sensors. Calculating the rate of change of frequency (RoCoF) used to generate a compensatory power injection from A

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Fig: I: Dynamic frequency response structure for virtual inertia control battery-based ESS used to store and release energy dynamically to emulate inertia.

A. Mathematical Equations

To address the mitigation of frequency impacts of renewable energy sources using virtual inertia control, a comprehensive set of mathematical equations that model the system dynamics and control strategy are presented.

(1). Traditional Swing Equation: The frequency dynamics of a power system without virtual inertia are governed by the swing equation:

$$2H\frac{d\Delta f}{dt} = \Delta P - D\Delta f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where:

H is System inertia constant (s), Δf is Frequency deviation (Hz), ΔP is Power imbalance (Pu), D is Damping coefficient (Pu/Hz).

(2). Virtual Inertia Control Law: The virtual power P_{virt} injected by renewable sources is proportional to the Rate of Change of Frequency (RoCoF) and frequency deviation:

$$P_{virt} = K_{In}\frac{d\Delta f}{dt} + K_d\Delta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where:

K_{In} is Virtual inertia gain (s)

K_d is Virtual damping gain (pu/Hz)

(3). Modified Swing Equation with Virtual Inertia: Incorporating P_{virt} into the swing equation:

$$(2H + K_{In}) + \frac{d\Delta f}{dt} + (D + K_d)\Delta f = \Delta P \ldots\ldots (3)$$

This equation shows enhanced effective inertia $2H + K_{In}$ and damping $D + K_d$.

(4). Transfer Function Representation: In Laplace domain, the system response to power imbalance becomes:

$$\Delta f(s) = \frac{1}{(2H + K_{In})s + (D + K_d)}\Delta P(s) \ldots\ldots (4)$$

These highlights improved stability with shifted poles.

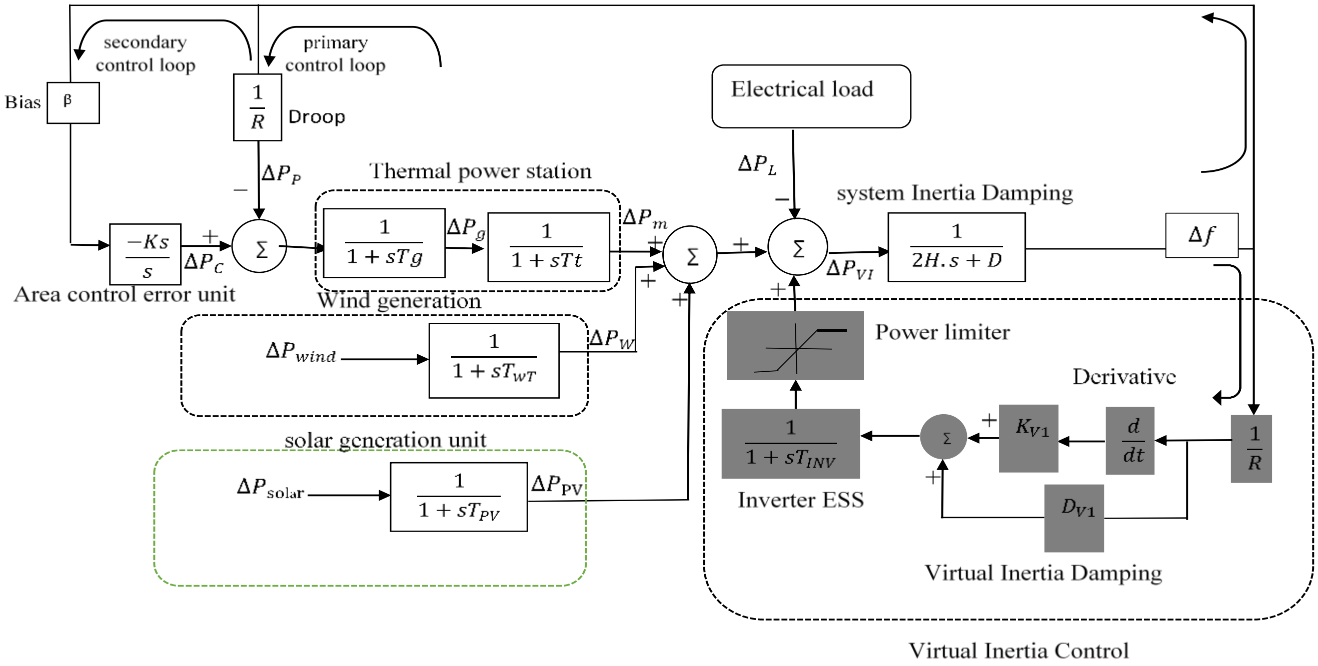
(5). Washout Filter For Derivative Term: To avoid noise amplification, a washout filter is applied to the RoCoF measurement:

$$G_{wshout}(s)\frac{s\tau}{1 + s\tau} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where τ is the filter time constant. The filtered virtual power becomes:

$$P_{virt}(s) = K_{In}\frac{s\tau}{1 + s\tau}\Delta f(s) + K_d\Delta f(s) \ldots\ldots\ldots (6)$$

(6). Energy Storage Dynamics: The energy storage systems' capacity is a key factor, defined as the maximum energy that can be discharged in a single cycle by the cell. The State of Charge (SOC) of the battery is expressed as the proportion of the



remaining capacity to the battery's total rated capacity.

Equation (7) illustrates the change in SOC (dSOC), which varies based on time and the capacity $\mathrm{C_i}$.

$$\mathrm{dSOC_{ESS}} = \frac{idt}{\mathrm{C_i}} = \mathrm{SOC_{ESS}} - \int \frac{idt}{\mathrm{C_i}} \dots\dots\dots.(7)$$

(7). Power Injection Constraints: The virtual power is bounded by the converter's capacity:

$$-P_{max} \le P_{virt} \le P_{max} \dots\dots\dots\dots\dots\dots\dots\dots\dots..(8)$$

(8). Multi-Source Coordination: For N virtual inertia sources, total contributions sum becomes

$$P_{virt.total} = \sum_{i=1}^{N} \left(K_{In,i} \frac{d\Delta f}{dt} + K_{d,i} \Delta f \right) \dots\dots\dots.(9)$$

(9). Optimal Gain Tuning: Using pole placement or optimization to select K_{In} and K_d:

$$\text{Minimize} \int_0^{\infty} (\Delta f^2 + \rho P^2{}_{virt}) dt \dots\dots\dots\dots(10)$$

where ρ penalizes control effort.

III. RESULTS AND DISCUSSIONS

The results and analysis of the impact of virtual inertia control (VIC) on mitigating frequency deviations in a renewable energy-integrated power system is presented. The objective is to evaluate how VIC improves system stability by reducing frequency deviations and the Rate of Change of Frequency (RoCoF) during disturbances. The results are obtained through MATLAB/Simulink simulations, where different scenarios are analyzed to demonstrate the effectiveness of VIC in stabilizing frequency fluctuations caused by renewable energy variability and sudden load changes.

A. *Frequency Response Without Virtual Inertia*

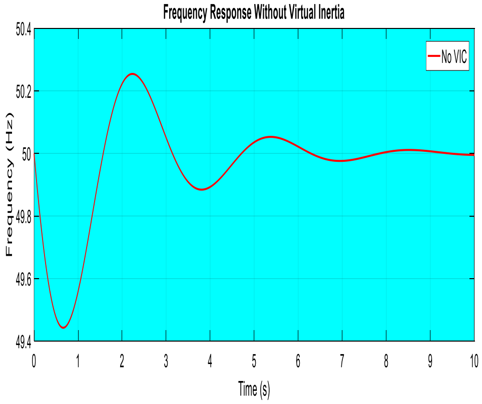


Fig. II: Frequency Response of the power system when subjected to a sudden load change without VIC.

The sudden increase in load results in a frequency dip as the power system reacts to balance supply and demand. Figure II shows the frequency response of the power system when subjected to a sudden load change without VIC. The frequency drops significantly Showing a deeper frequency dip (greater deviation) indicating poor frequency support due to the lack of inertia below nominal reaching 49.4Hz, with an initial Rate of Change of Frequency (RoCoF) of -1.6Hz/s which is very high, more oscillations and takes longer to stabilize indicating instability with a settling time of 8 second.

B. *Frequency Response with Virtual Inertia Control*

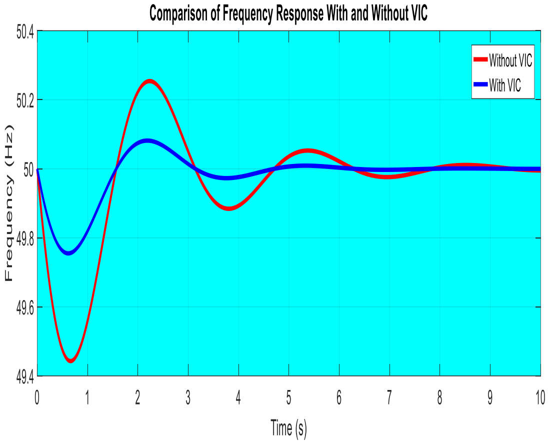


Fig. III: Comparison of Frequency response with and without VIC

Fig. III illustrates the system's response when VIC is implemented, compared to the base case, the frequency deviation is reduced, and the RoCoF is lower, indicating improved system stability. The simulation time spans from 0 to approximately 10 seconds, representing the deviation of system frequency from its nominal value (per unit). The scale ranges from 50.4Hz to 49.4Hz, the red Line is a plot without Virtual Inertia showing the frequency deviation when no virtual inertia is applied. It exhibits higher oscillations and overshoot, meaning the system struggles more to stabilize frequency. Blue Line (With Virtual Inertia) represents the system response when virtual inertia control is implemented. The frequency deviation is smaller with a maximum frequency deviation of 0.4Hz and dampens faster, initial RoCoF is -0.8Hz/s with a settling time of 5.71s indicating better frequency stability. The frequency dip is less severe, oscillations are dampened, and the system returns to nominal frequency more quickly demonstrating the effectiveness of virtual inertia in mitigating frequency deviations. Virtual inertia helps reduce frequency deviations and improves system stability. Without virtual inertia, the system experiences greater oscillations and takes longer to stabilize. A sudden load increase causes a frequency dip, and the system must respond quickly to maintain stability. This plot effectively shows why virtual inertia is crucial in modern power systems with a high penetration of renewable energy sources that lack physical inertia.

C. Impact of Renewable Energy Penetration

To analyze the impact of VIC under different renewable energy penetration levels, simulations are performed at 30%, 50%, and 70% renewable energy penetration. Figure 4.3 shows that as renewable penetration increases, frequency deviations become more significant without VIC, but with VIC, the system maintains better stability.

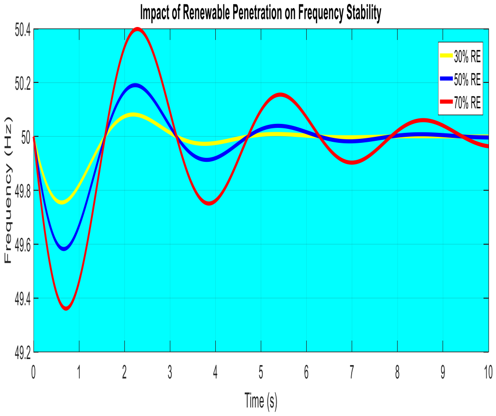


Fig. IV: Impact of Renewable Energy Penetration on Frequency stability

D. Performance Analysis

TABLE I:

IMPACT OF RENEWABLE ENERGY PENETRATION

Renewable Penetration	Frequency Nadir (Hz/s)	Rate of Change of Frequency (RoCoF)	Settling Time (s)
30% RE	49.7	-0.25	6
50% RE	49.5	-0.35	8
70% RE	49.2	-0.45	10

Table I. shows that Higher renewable penetration increases frequency instability, requiring better inertia support. At 30% penetration, frequency deviations were moderate, but at 50% and 70% penetration, the system experienced more significant instability. VIC proved effective in mitigating these effects by providing synthetic inertia to compensate for the reduced natural inertia.

E. Optimization-Based Virtual Inertia Control

An optimized VIC using Particle Swarm Optimization (PSO) and Battery Energy Storage System (BESS) is implemented. The results in Figure 4.4 indicate that optimized VIC provides even better frequency stability, reducing frequency deviation and RoCoF more effectively than conventional VIC.

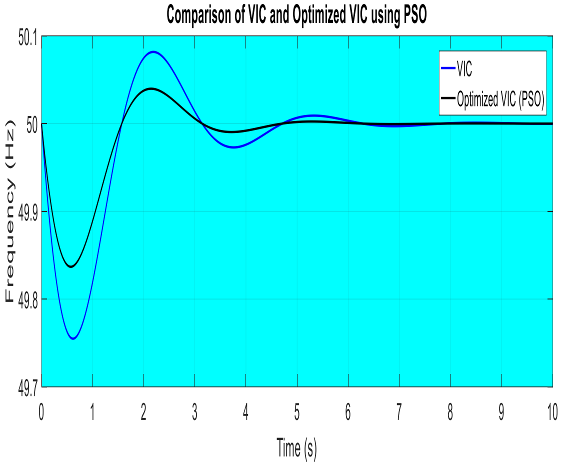


Fig. V: Comparison of VIC and optimized VIC using Particle Swarm Optimization (PSO)

Fig. V compares virtual inertia Control (VIC) and Optimized VIC (using PSO), the plot show that the frequency deviation of the blue line (VIC) is 0.4Hz while that of the optimized VIC is 0.3Hz, the optimized VIC (black line) reduces the maximum frequency deviation from 0.4Hz to 0.3Hz, meaning better frequency stability. the settling time of the blue line (VIC) is 5.71s while that of the optimized VIC is 4.44s, the optimized VIC (black line) reduces the settling from 5.71s to 4.44s, meaning faster frequency recovery. The optimized VIC reduces RoFoC from -0.8Hz/s to -0.6Hz/s, meaning a smoother frequency change. The Optimized VIC (PSO-based control) improves system stability by reducing frequency deviation, lowering RoCoF and achieving faster frequency recovery.

F. Comparison of Key Performance Indicators

A summary of the key performance indicators for different scenarios is presented in Table II.

TABLE II:

PERFORMANCE COMPARISON OF DIFFERENT SCENARIOS

Scenario	Frequency Nadir (Hz/s)	Rate of Change of Frequency (RoCoF)	Settling Time (s)
Without VIC	49.2	-0.5	10
With VIC	49.6	-0.3	5.71
High Renewable (70%)	49.2	-0.45	10
With Optimized VIC (PSO)	49.8	-0.2	4.44

From Table II, it is observed that VIC significantly improves frequency stability by increasing the minimum frequency (nadir), reducing RoCoF, and decreasing the time required for frequency recovery. The optimized VIC further enhances these benefits.

The results demonstrate that VIC effectively mitigates frequency deviations in power systems with high renewable energy penetration. The findings highlight the following: Without VIC, the system experiences severe frequency deviations, high RoCoF, and prolonged instability. With VIC, frequency deviations are reduced, and RoCoF improves, leading to a more stable system. Higher Renewable Energy Penetration without VIC results in increased instability. However, VIC helps maintain stability even with higher renewable energy contributions. Optimization using PSO further refines the VIC parameters, leading to better frequency regulation and system resilience.

IV. CONCLUSION

This paper focused on mitigating frequency impacts on renewable energy sources using Virtual Inertia Control (VIC) for optimal power system operations. With the increasing integration of renewable energy sources such as wind and solar, conventional synchronous inertia is being reduced, leading to frequency instability, higher Rate of Change of Frequency (RoCoF), and larger frequency deviations. To address these challenges, VIC was implemented and optimized using Particle Swarm Optimization (PSO) to enhance grid stability. This work investigated the effectiveness of VIC in enhancing frequency stability in power systems with high RES penetration. Through simulation studies, it was demonstrated that VIC can significantly improve the Rate of Change of Frequency (RoCoF) and reduce frequency nadir following disturbances. The control strategies, including droop control and inertia emulation, were analyzed, showing that proper tuning of virtual inertia parameters is crucial for optimal performance. The findings confirm that VIC can enhance grid resilience, ensuring smoother frequency regulation even under high renewable energy penetration. However, the effectiveness of VIC depends on the control algorithm, energy storage support, and system dynamics. Thus, while VIC presents a viable solution, its implementation must be carefully optimized to match specific grid conditions. The study demonstrated how VIC plays a crucial role in improving frequency stability by providing synthetic inertia, which slows down frequency deviations after disturbances. Without VIC, the system experienced high RoCoF and deep frequency deviations after disturbances, whereas VIC effectively reduced these impacts ensuring that the system remains above the critical frequency threshold. The simulations showed that higher renewable energy penetration leads to greater frequency instability due to reduced system inertia. At 30% penetration, frequency deviations were moderate, but at 50% and 70% penetration, the system experienced more significant instability. VIC proved effective in mitigating these effects by providing synthetic inertia to compensate for the reduced natural inertia. The application of PSO-based VIC tuning further enhanced frequency stability. Compared to standard VIC, PSO-optimized VIC reduced frequency nadir, improved settling time, and provided a more adaptive response to system fluctuations. The optimized VIC system outperformed conventional VIC, achieving a lower RoCoF (-0.6 Hz/s compared to -0.8 Hz/s) and a faster settling time (4.44s compared to 5.71s). Overall, the results confirm that Virtual Inertia Control, especially when optimized using PSO, is a powerful tool for mitigating frequency impacts in renewable energy-based power systems, ensuring improved stability, reliability, and optimal operation of modern power grids.

References

[1] Grazioli, G.; Chlela, S.; Selosse, S.; Maïzi, N. 2022. The Multi-Facets of Increasing the Renewable Energy Integration in Power

Systems. Energies 2022, 15, 6795. https://doi.org/10.3390/en15186795

[2] Le Hong L., Le Khoa N., Nguyen Khac T. D. and Nguyen, H. H. 2024. Two-Area Automatic Generation Control for Power Systems with Highly Penetrating Renewable Energy Sources Electronics 2024, 13(15), 2907; https://doi.org/10.3390/electronics13152907

[3] K. Pathak, A. K. Yadav, S. Padmanaban and I. Kamwa, 2022,"Fractional Cascade LFC for Distributed Energy Sources via Advanced Optimization Technique Under High Renewable Shares," in IEEE Access, vol. 10, pp. 92828-92842 https://doi: 10.1109/ACCESS.2022.3202907.

[4] Fernando O., Georg E. 2017, Cross Border Impacts of Renewable Energy Sources in Central Western Europe. USAEE Working Paper No. 17-303 https://ssrn.com/abstract=2928823

[5] Zifan G. 2024 Study on frequency stability control strategies for microgrid based on hybrid renewable energy Science and Technology for Energy Transition 79, 54 https://creativecommons.org/licenses/by/4.0

[6] Francis M., Jackson J. J., Eun-Kyung K., Ton D. D., Jin-Woo J. 2014. Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration Renewable and sustainable energy reviews 34, 501-516.

[7] K. Yan, G. Li, R. Zhang, Y. Xu, T. Jiang and X. Li, 2024 "Frequency Control and Optimal Operation of Low-Inertia Power Systems with HVDC and Renewable Energy: A Review," in IEEE Transactions on Power Systems, vol. 39, no. 2, pp. 4279-4295, doi: 10.1109/TPWRS.2023.3288086.

[8] Hasen, S.A., Aydın, Ö., Ayasun, S. 2024. Impact of virtual inertia and damping control on stability delay margins of load frequency control systems with renewable energy sources. Electr Eng 106, 323–341. https://doi.org/10.1007/s00202-023-01984-3

[9] Dumrul Y, Bilgili F, Dumrul C, Kılıçarslan Z, Rahman MN. 2023. The impacts of renewable energy production, economic growth, and economic globalization on CO2 emissions: evidence from Fourier ADL co-integration and Fourier-Granger causality test for Turkey. Environ Sci Pollut Res Int. 2023 Sep;30(41):94138-94153. https://doi: 10.1007/s11356-023-28800-6.

[10] Ulbig, A., Borsche, T.S., & Andersson, G., 2014 Impact of low rotational inertia on power system stability and operation. IFAC Proceedings Volumes. 47(3), 7290-7297

[11] Tielens, P., & Van Hertem, D., 2016 The relevance of inertia in power systems. Renew. Sustain. Energy Rev. 55, 999-1009

[12] Bevrani, H., Ise, T., & Y. Miura, 2014 Virtual synchronous generators: a survey and new perspectives. Int. J. Electr. Power Energy Syst. 54, 244–254

[13] Tamrakar, U., Shrestha, D., Maharjan, M., Bhattarai, B., Hansen, T., & Tonkoski, R. 2017 Virtual inertia: current trends and future directions. Appl. Sci. 7(7), 654

[14] Wang, Y., Silva, V., & Lopez-Botet-zulueta, M., 2016 Impact of high penetration of variable renewable generation on frequency dynamics in the continental Europe interconnected system. IET Renew. Power Generation. 10(1), 10-16

[15] Zhong, Q. C., Nguyen, P. L., Ma, Z. & Sheng, W. 2014 Self-synchronized synchronverters: inverters without a dedicated synchronization unit. IEEE Trans. Power Electron. 29(2), 617-630

[16] Sakimoto, K., Miura, Y., & Ise, T., 2011 Stabilization of a power system with a distributed generator by a Virtual Synchronous Generator function, in Proc. International Conference on Power Electronics, 1498–1505

[17] Liu, J., Miura, Y. & Ise, T. 2017 Enhanced virtual synchronous generator control for parallel inverters in microgrids. IEEE Trans. Smart Grid 8(5), 2268–2277

[18] Alipoor, J., Miura, Y., & Ise, T. 2015 Power system stabilization using virtual synchronous generator with alternating moment of inertia. IEEE J. Emerg. Sel. Top. Power Electron. 3(2), 451–458

[19] Liu, J., Miura, Y. & Ise, T. 2016 Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators. IEEE Trans. Power Electron. 31(5), 3600–3611

[20] Torres, M. &. Lopes, L.A. C., 2009 Virtual synchronous generator control in autonomous wind-diesel power systems, in Proc. IEEE Electrical Power and Energy Conference, 1-6

[21] Liansong, X., Xiaokang, L., Hongqing, L. & Yonghui, L., "Performance Comparison of Typical Frequency Response Strategies for Power Systems with High Penetration of Renewable Energy Sources". IEEE MANUSCRIPT FOR PEER REVIEW

[22] Shobug, A., Nafis A. C., Alamgir H., Mohammad J. S, Junwei Lu & Fuwen Y. 2024 " Virtual Inertia Control for Power Electronics-Integrated Power Systems: Challenges and Prospects" Special Issue Energy, Electrical and Power Engineering Energies 2024, 17(11), 2737; https://doi.org/10.3390/en17112737

[23] Ana F. G, Emilio G.-L., Eduard M. & Ángel M.G. 2020 "A Review of Virtual Inertia Techniques for Renewable Energy-Based Generators" May 2020 DOI: 10.5772/intechopen.92651

[24] Thongchart K., Fathin S. R. & Yasunori M. 2021"Virtual Inertia Synthesis and Control" text book. Pages XXII, 259 [273]