Virtual inertia evaluation for frequency instability in renewable energy integration

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ABSTRACT

In recent trends, the increasing integration of renewable energy sources (RES) into grids has provides a transition in electricity generation and distribution in terms of frequency instability. Recently, the concept of virtual inertia (VI) has developed as a promising solution to minimize frequency instability in interconnected RES. Therefore, this research introduces VI evaluation technique to decrease the frequency instability. Advanced control algorithms are used to create VI, which simulates the stabilizing effect of traditional rotating mass in conventional power systems. The high penetration of RES based on power converters has suggestively decreased the VI which making them susceptible to frequency instability. This work recommends another use of VI control to further develop recurrence dependability of the connected power framework because of high entrance level of RESs. Δf values differ between 17.4215 and 20.3621 with significant frequency variations due to conventional control. Equally, VI control exhibits a high level of efficiency in reducing frequency deviations; The Δf values were consistently smaller between 0.0236 and 0.0369 than the conventional control. These findings signify the potential of VI control to improve frequency stability in power systems with RES.

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1. INTRODUCTION

The method that renewable energy sources (RES) like solar and wind-are being integrated into traditional power grids, has drastically changed how the world's energy systems operate. Although switching to more sustainable and clean energy is necessary, the intermittent nature of RES poses problems for grid stability, especially with regard to frequency instability [1], [2]. In order to ensure frequency stability, conventional power systems have depended on the intrinsic inertia of rotating masses in synchronous generators. However, new tactics are needed to guarantee the dependable operation of power grids as these conventional sources are being replaced by renewable alternatives with little to no inertia. The term "virtual inertia (VI)" describes how power electronics and sophisticated control techniques may simulate the stabilizing effects that rotating masses often give [3], [4]. Control and stabilization techniques must change to accommodate the integration of RES and VI appears to be a viable way to reduce frequency variations and preserve grid stability. Modern power grid dynamics are being altered by the continual shift towards RES, which provide a sustainable substitute for traditional fossil fuels [5], [6]. The frequency instability that grids are experiencing is one of the main issues brought forth by this shift. Synchronous generators' revolving masses have historically been essential for supplying inertia, which helps power systems maintain their inherent stability by withstanding sudden frequency fluctuations. The loss of inertia becomes a critical concern when renewable energy systems like solar and wind do not have these rotating masses [7], [8].

The difficulty in incorporating renewable energy into current power grids arises from the paradigm shift towards sustainable energy sources, which is motivated by the need to reduce greenhouse gas emissions and address environmental issues. RES like wind and solar have intrinsic fluctuation and intermittency, unlike traditional power generation [9]. Maintaining grid stability becomes more difficult as a result of the unpredictable nature of the electrical supply and demand [10]. Innovative grid management techniques are required due to the unpredictability of renewable energy production in order to control abrupt increases or decreases in power output and maintain a steady and dependable supply of electricity. A cleaner, more sustainable energy future depends on finding practical ways to balance the erratic nature of RES with the needs of the electrical grid [11], [12].

Power system stability has long been based on traditional inertia, which has historically been supplied by the revolving masses of synchronous generators. Because they resist sudden variations in power, these rotating masses serve as a reservoir of kinetic energy, assisting in the grid's ability to maintain a constant frequency [13], [14]. The intrinsic inertia that has historically stabilized power systems is reduced by RES like wind and solar, which do not have these revolving masses like fossil fuel-based generators do [15], [16]. The grid's resilience against abrupt variations in supply and demand is thus jeopardised. When renewable energy supply is low, this constraint is especially noticeable since the grid is more vulnerable to frequency fluctuations due to the lack of traditional inertia [17], [18]. To confirm the sustained stability and dependability of a changing energy landscape, it is imperative to recognize and address the limitations of traditional inertia in the context of renewable energy integration. In the age of renewable energy supremacy, novel approaches like VI are emerging to offset this loss and improve grid stability [19]. The first work by Abbou *et al.* [20] investigated the field of energy storage systems (ESS) and superconducting magnetic energy storage (SMES) in VI control. The work, presented at the International Conference on Artificial Intelligence in Renewable Energetic Systems, emphasized frequency augmentation as a crucial element of power system stability. The authors offered a novel approach, VI control to report the issues caused by widespread use of renewable energy. This work presented potential strategies for enhancing grid stability, providing practitioners and academics with a feasible route forward. Ahmed *et al.* [21] provided a study on dynamic grid stability in low-carbon power systems with negligible inertia in 2023. This research explained the challenges that reduced inertia in low carbon power systems presents. It was published in renewable energy. The authors explored the challenges of maintaining grid stability in the face of a changing energy environment. Their results significantly improved the present discourse about the challenges posed by low-carbon power systems and established the foundation for additional study in this important topic. Al Kez *et al.* [22] introduced research addressed the challenges and mitigation techniques associated with integrating inverter-based resources and was published in IET smart grid. The authors provided an in-depth examination of several approaches to frequency management, laying the groundwork for understanding the difficulties involved in running power networks that contain a sizable amount of renewable energy. In order to initiate their investigation, Ayamolowo *et al.* [23] first identified and analyzed the gaps in the integration of RES into current infrastructure. The study offered a thorough analysis of the difficulties encountered in this field, highlighting how crucial it was to resolve these problems in order to successfully implement RES. With skill, this study examined the many obstacles: technological, governmental, and infrastructure-related, so as to provide a comprehensive picture of the situation. Ayamolowo *et al.* [24] refocused their attention in their 2022 book on the crucial idea of inertia in modern renewable energy-based systems. The study discussed the particular needs and difficulties in preserving grid stability, a problem made worse by the sporadic nature of RES. The writers also made a substantial contribution to the current discussion concerning the dependability and robustness of renewable energy systems by examining the need for inertia in these networks. The main contributions are denoted as follows;

- Advanced control mechanisms can be used to create VI, which mimics the stabilizing effect of traditional rotating mass in conventional power systems.
- With the sharp rise in the use of force converter-based RESs, complete structural inertia of the interrelated power framework can be impressively diminished, making structure more vulnerable to structural instability.
- This work suggests another application of VI control to solve the problems caused by large loss of structure inertia to further improve the repeatability, reliability of power structure because of high threshold level of RESs.

This research paper is structured as follows: the proposed method is defined in section 2. Multi-region power framework with VI control is defined in section 3. Result and discussion are defined in section 4. The conclusion is given in section 5.

2. PROPOSED METHOD

In this section, RES is both intermittent and requires fast-responding inverters to synchronize with the grid to be able to store electrical energy and be utilized at a later time, with the RES to the grid seen as the fast-dynamic response. This occurs due to duration and the formation of an impact or a loss of phase angle and instability of voltage. Reduction of frequency stability ensues through insufficiency of rotating masses, partly due to RES decomposition into a DC current through the conventional inverter. It generates larger shifts of the frequency and voltage distortions in the case of disruption of the power supply. Viable solutions for the problem of connected RES are VI or artificial inertia and artificial control strategy. As a new inverter parameter, VI contributes to more stability, and by far has greatly analyzed in inertia of conventional generators. VI is analogous to SM's under PWM simulation through inertia. Figure 1 represents the overall connectivity of VI in grid-integrated RES.

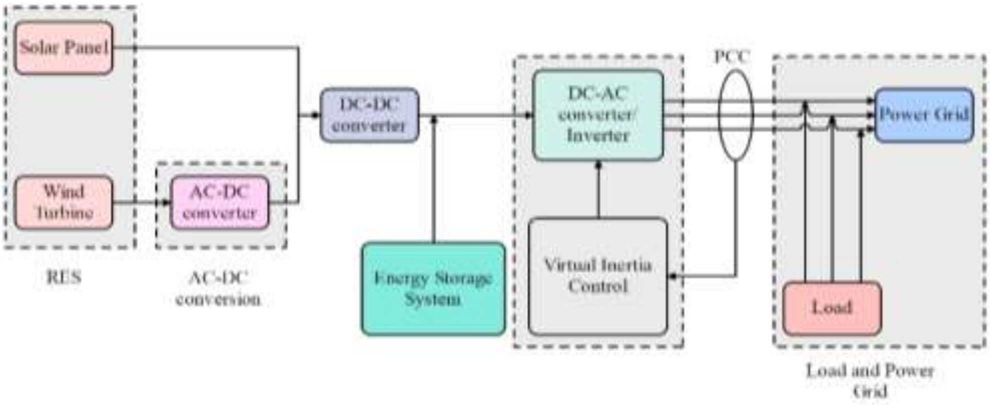

Figure 1. General connection of grid-connected RES

2.1. Concept of virtual inertia control

The VI is a significant point of VSG which is designed to address the deficiency by utilizing an injection model. The default operations restrictions of VI approach cannot offer dependable frequency provision. Generally, the setup in VI control comprises of derivative component as developed controller $K(s)$, VI control and power limiter ($\Delta P_{inertia_{max}}$, $\Delta P_{inertia_{min}}$). The push for the regular power framework to grow the quantity of non-simultaneous generators, (for example, RES) is the shift to a low-carbon local area. These generators for the most part use power convertors as the matrix network interface. To further develop framework inertia and recurrence dependability, VI control copies the central player's way of behaving. If dynamic power through force electric converters of energy stockpiling structures (ESS) is substantially limited through subordinate of framework recurrence, then VI control is virtually derived. This assists with working on the framework's inertial reaction against varieties in RESs entrance and power interest. The emulation of power p is formulated in (1) as follows;

$$p_{Emulate=k_c} f_0 \frac{d(\Delta f)}{dt} \quad (1)$$

where, k_c signifies the proportionate change contingent upon converter gain, f_0 addresses the ostensible recurrence of the framework. Nevertheless, inertia response is a quick reaction within the power system to the power imbalance, as the stored energy within the energy buffer structures is actively absorbed or released. The energy buffer techniques through inertia response of RES-intensive grid plug the wind turbines (blades, generator and gearbox), capacitors in power electronic converters and energy storage devices. The study likewise creates an energy buffer framework as a probable method to combat power imbalance actively. Therefore, the system also provides inertia, unlike the VI control approaches which are used for overcoming the low inertia difficulties common in RES-dominated power system, as presented in Figure 2. These techniques are further classified as frequency control or virtual synchronous generator (VSG) control methods according to the control theory principal, because these techniques have different inertia and thus vary the system response.

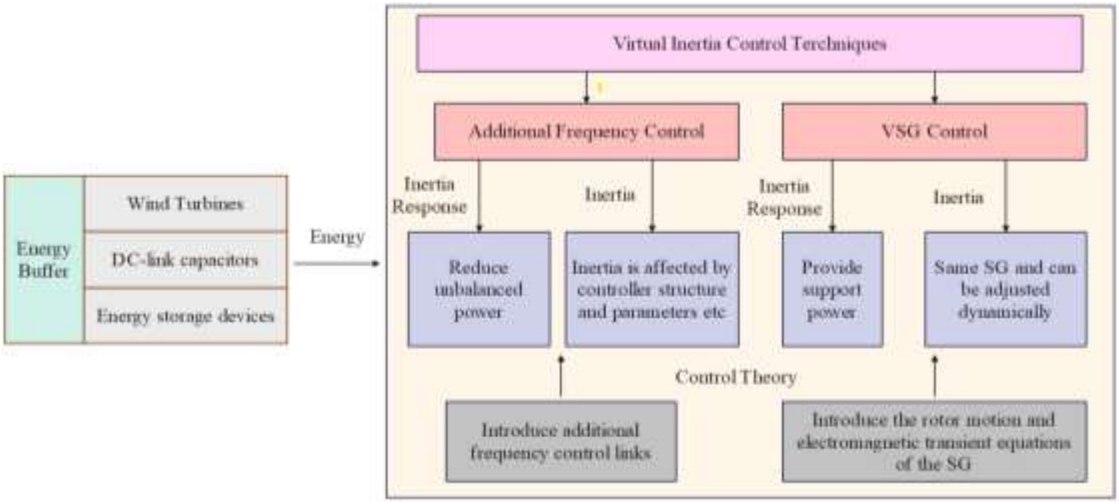

Figure 2. Block diagram of VI control

3. MULTI-REGION POWER FRAMEWORK WITH VIRTUAL INERTIA CONTROL

The distinct layout and regulation anticipated to produce enough VI -based converters are depicted in Figure 3. The subordinate control strategy that calculates the rate of progress of recurrence (ROCOF) to shift a supplementary capacity to a predetermined location in area I during RESs entrance and possibility, is the main idea underlying VI control [25]. However, the subsidiary control strategy is exceptionally helpless to recurrence estimation clamor. A low pass channel is utilized to control the framework to get around this issue. Moreover, the low-pass channel introduces the ESS's dynamic ways of behaving. Thus, VI control helps an interconnected power framework by causing the RESs in that framework to have inertia power equivalent to simultaneous generators used in conventional power frameworks. Therefore, administrators recommended VI provides the inertia trademark, which adds complete inertia to the interconnected power structure and improves repeatability reliability and execution. In this work, we proposed that the ESS could produce VI power in the two areas. The suggested control supplies the expected capacity to the I^{th} region during the recurrence deviation in the way portrayed underneath.

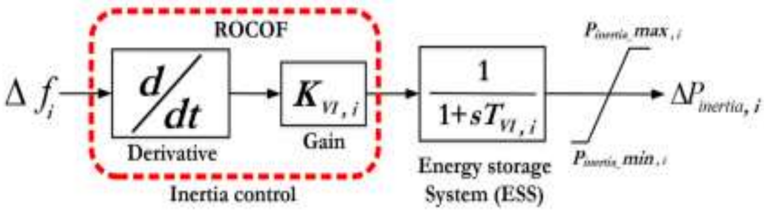

Figure 3. Dynamic model of the controller that was created to simulate VI

Ultimately, ROCOF is established by the suggested inertia control system through the subsidiary control process; the inertia power is recreated by the VI gain (KVI) modifying the ESS's dynamic power reference. Consequently, the special model of a multi-region framework is addressed by modifying to include VI (also known as imitated power). The recurrence deviation for region i should be determined using the preceding recipe, taking into account the age/load power signals, inertia power signals, and tie-line power signals as represented in (2).

$$\Delta fi = \frac{1}{2H_{is}+D_i} (\Delta p_{mi} + \Delta p_{wi} + \Delta p_{si} + \Delta p_{inertial,i} - \Delta p_{Li} - \Delta p_{Tie,i}) \quad (2)$$

Where, the recurrence deviation in region i is addressed by Δfi. In region i, this approach addresses the consistent of inertia while Δp_{mi} addresses the power created by the warm creation unit. D_i is the region i damping coefficient, and $+\Delta p_{wi}$ is the region i created power from the breeze ranch. Δp_{si} is the region

i created power from the sunlight-based ranch. $\Delta p_{inertial,i}$ is the region i copied inertia power from the ESS unit, Δp_{Li} is the region i heap changes, and $\Delta p_{Tie,i}$ is the region i general tie-line AC power changes.

4. SIMULATION RESULTS AND DISCUSSIONS

Reproduction consequences of the proposed control strategy are canvassed in this part. The MATLAB/Simulink® developer is utilized for the recreation studies, incorporating all the part subtleties (Figure 3 and Table 1) under undeniable level activities of the framework's essential and optional regulators. The findings and discussion are isolated into two sections: the first one tends to study how an interconnected structure behaves when obtaining VI control, which includes inertia. The second tends to study how the structure responds dynamically to extreme test conditions when VI control is applied. The recommended control procedure promptly adjustable to greater power frameworks on the grounds of that the connected framework in this review is examined and mimicked on for every unit premise, and the decision of framework base makes little difference to the reproduction's outcomes.

4.1. Eigenvalue examination of virtual inertia control

For connected power frameworks, the unique effects of VI are analyzed utilizing the subordinate control method. The essential objective of this part is to analyze the important impact that gains of VI control (KVI1, KVI2) have on framework's exhibition, alongside the dependability. Subsequently, interconnected power framework's eigenvalue direction is found for various KVI1 and KVI2 boundary varieties. Since the majority of the eigenvalues are situated far to one side of the s-plane and have negative genuine parts, the framework turns out to be steadier when the control gain KVI1 is expanded. An unreasonable expansion in control gain KVI1 causes the sixth and seventh modes (λ6) to move back to right half of s-plane that adversely influences the framework's exhibition. Since the majority of eigenvalues shift distant to left half of s-plane, the results show how cumulative control gain KVI2 help framework achieve further reliability and fewer oscillation. Alternatively, it is evident that when advanced control gain of KVI2 is applied, distinct approaches (λ3, λ4) migrate towards right of s-plane. Further, this prompts a decrease in the unique solidness and execution of the interconnected power framework. In rundown, picking the VI control gain ideally includes making compromises to get the most ideal reaction from the interconnected power framework in these circumstances. Table 1 shows tabulation for eigen value trajectory of VI control in area-1.

Table 1. Dominant poles' eigenvalue trajectory across changes in gain of VI control in area-1

Real	Image
2.3	1.5
1.5	1.3
2.5	2.6
3.2	3.5
4.0	6.2
5.3	4.1
3.2	2.3

The actual image data that is supplied is a set of paired values, each of which consists of two numerical measurements. Within the framework of image processing or analysis, these pairs are associated with distinct attributes or features that are retrieved from images. For example, the first value in each pair corresponds to a certain quality or attribute of a picture, while the second value denotes a different connected aspect. Some patterns and trends emerge when the data is examined more closely. Variability in the values points to a diversity of images under analysis. For example, in the third pair, the related picture feature shows a modest positive improvement, increasing from 2.5 to 2.6. Conversely, the fifth pair exhibits a more notable shift from 4.0 to 6.2, indicating a considerable modification in the related image attribute Together, the data points illustrate the dynamic nature of images under evaluation. These discrepancies are a sign of different content, different lighting, or other elements influencing the characteristics under assessment. Understanding the general traits and attributes of the photos in the dataset requires analyzing these changes. It is crucial to remember that a more thorough interpretation is difficult in the absence of other context regarding the precise qualities being examined, or the characteristics of the photographs. Nonetheless, the information supplied establishes the groundwork for more research and examination, offering a point of departure for examining the connections among various characteristics in the collection of pictures. Table 2 represents the dominant poles eigenvalue trajectory in VI control gain in area-2.

Table 2. Dominant poles' eigenvalue trajectory across changes in gain of VI control in area-2

Image	Real		
	Maximum	Minimum	Optimum
1.2	2.3	1.6	1.8
2.3	2.5	2.5	2.5
4.2	2.6	3.4	1.2
5.3	4.1	4.1	3.6
6.1	3.5	4.8	2.4
2.8	4.2	5.3	2.3

4.2. Abrupt load change

An interconnected power structure to focus on this situation is used as a test structure to show how successful the control process is this. The recommended control technique is tried in region 1 with 1.5 MW step load variation ($\Delta PL = 0.1 p.u.$). The undeniable level tasks of essential and auxiliary controls, additionally alluded to as the traditional control are stood out from the recommended control method to survey its proficiency. The recurrence deviation in region 1, the recurrence variation in region 2, as well as the tie-line power variation are the outcomes going down to the base. The VI control framework beats the ordinary control framework concerning solidness and speed in both typical and low inertia situations. Table 3 represents the systematic reaction of typical system inertia.

Table 3. System reaction when there is typical system inertia

Time	Conventual control	Virtual inertial control
1.2	2.5	2.6
2.3	1.4	1.5
3.2	2.1	2.6
4.1	3.5	3.4
2.5	2.4	4.1
2.4	3.6	2.0
1.6	4.2	3.5

A comparison of time measurements for two distinct control strategies - conventional control and VI control is shown in the accompanying table. The columns 'time,' 'conventional control,' and 'virtual inertial control' have corresponding values for each approach, and each row denotes a distinct time measurement. The effectiveness and performance of the two control strategies is comprehended in various settings by analyzing this data. First, a closer look at the 'conventional control' column reveals information on the time intervals connected to the conventional control strategy. The VI control method works in comparable cases by comparing this with the 'VI control' column. The VI control time measurement in the first row is 2.6 units. Through this comparison, in the given circumstances, the VI control approach is more or less time-efficient than the conventional control method. This suggests that the conventional control method is slightly more time-efficient in the particular scenarios the data depict. It is crucial to remember how these data are interpreted vary depending on the particular context and specifications of the system or process under control. Moreover, the data presented does not directly capture factors that are important in selecting the best control mechanism, such as precision, stability, or flexibility.

4.3. Raised degree of renewable energy invasion and request

Table 4 displays the performance analysis of operating time and capacity with respect to disturbance sources. Also, table 4 shows how these extreme operations verify the durability of the proposed control method against changes in system inertia, high-level RES/load penetration, as well as the real operation's significant dynamic impact of linked power systems. Hence, such a thorough test situation plentifully delineates the effect of huge RES entrance on the general recurrence, alongside tie-line power conduct of framework in interconnected power.

Table 4. Distinct disturbance mechanisms within the networked power grid

Disturbance source	Operating time (s)	Capacity (MW)
Area-1 solar installation	512.01	3.82
Area-2 wind energy initiative (initial phase)	6.72	4.12
Area-1 power demand	231.01	6.71
Area-2 load requirements (initial phase)	31.12	3.12

The information supplied describes the capacity and operating time linked to various causes of disruption in a power system, with a particular emphasis on the load in area-1, the load in area-2 (initial state), the solar farm in area-1, and the wind farm in area-2 (initial state). The operational time values illustrate the temporal dimension of each disturbance source's influence, showing how long the system is influenced. The solar farm located in area-1, for instance, adds to the overall disturbance for 512.01 seconds during its operation. Increased capacity indicates an increased ability to impact the power system. During the designated operational time of 6.72 seconds, the wind farm in area-2 (initial state) has a significant impact on the system, as evidenced by its notable 4.12 MW capacity. When the data is interpreted as a whole, it becomes clear that every source of disturbance has a different operating duration and capacity, adding to the overall dynamics and difficulties the power system faces. For example, compared to the wind farm in area-2 (initial condition), the load in area-1 has a longer working time (231.01 seconds), but its capacity is larger at 6.71 MW. This implies that the electricity system is significantly and persistently impacted by the load in area-1. The information offers a quantitative framework for assessing the relative impact of various disturbance sources, facilitating well-informed choices for response tactics and system optimization. To gain a more comprehensive understanding of the effects of each disturbance source on the power system, more analysis and contextual information on the unique characteristics of each source is required. Table 5 shows the system's absolute maximum frequency deviation when the system's inertia is fixed at low, medium, and high levels and there are significant load variations.

Table 5. The connected system's assessment index for frequency deviation

Case study	Δf 1 (Conventional control)	Δf 2 (Conventional control)	Δf 1 (VI control)	Δf 2 (VI control)
High system inertia (95%)	0.03121	0.03125	0.0369	0.0369
Medium system inertia (50%)	17.4215	18.0231	0.0369	0.0302
Low system inertia (30%)	18.2305	20.3621	0.0236	0.0325

The Table 5 demonstrates that maximum system frequency deviations occur when the system's inertia decreases. Higher frequency deviation is shown when medium and low system inertia circumstances are encountered, as traditional control is unable to sustain the frequency deviation. Using both conventional control and VI control, the case study data supplied compares frequency deviations (Δf) in a power system under various scenarios of system inertia. The capacity of a power system to withstand frequency fluctuations is known as system inertia, and the departure from the nominal frequency is represented as Δf. The first two columns in the context of conventional control show Δf for two distinct buses (designated as Δf 1 and Δf 2) under situations of high (95%), medium (50%), and low (30%) system inertia. For example, both Δf 1 and Δf 2 exhibit very minor variations of 0.03121 and 0.03125, respectively, with high system inertia (95%).

4.4. Discussion

This research provides a comprehensive framework for assessing the effectiveness of VI in reducing frequency instability in power systems with high penetrated RES. From the evaluation, it validates that the control offers a robust and adaptable solution for enhancing the frequency stability of integrated power systems. This suggests that the addition of VI, possibly via sophisticated control strategies or energy storage devices impact frequency deviations in a manner distinct from that of conventional approaches. In cases of medium and low system inertia, the biggest difference is evident. Under these conditions, there are significant frequency variations experienced by conventional control with Δf values varying between 17.4215 and 20.3621. Conversely, VI control exhibits a high degree of efficacy in reducing frequency deviations; Δf values are consistently smaller between 0.0236 and 0.0369 than the conventional control. This evaluation demonstrates the potential advantages of VI control, particularly in situations where the system's real inertia is constrained.

5. CONCLUSION

This research offers a novel application of subordinate control procedure based on VI control to improve the frequency performance and stability of interconnected RES. The proposed control strategy is effectively adaptable to a multi-region framework by considering size, intricacy, or different qualities. A comprehensive examination of the inertia control boundaries is done to show the genuine results of VI on framework execution and dependability. The evaluation displays that VI control suggestively minimizes the frequency deviations in the interconnected system during the disturbances. From the results evaluation, it clearly shows that Δf values vary between 17.4215 and 20.3621 with significant frequency variations due to conventional control. Similarly, the Δf values were consistently smaller between 0.0236 and 0.0369 than the conventional control. The VI control framework offers the required reliability and performance, contrary to high-RES input, critical load-resolving impacts, and low inertia image. From the overall evaluation, this research builds upon the existing works by presenting a comprehensive framework for evaluating the VI effectiveness in reducing frequency instability. In the future, an objective of VI evaluation will be enhanced to analyze various approaches for ensuring effective integration with renewable energy systems and grid stability. Furthermore, the results of this research emphasize the potential of VI control to develop the RES management in interconnected systems which paves the way for a more resilient and sustainable energy future.

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