



Impact of Virtual Inertia Emulation on AGC Performance in High-Penetration Solar Areas

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Abstract: *The global shift toward renewable energy has significantly increased the penetration of solar photovoltaics (PV) in modern power grids. However, the displacement of conventional synchronous generators by inverter-based resources (IBRs) leads to a reduction in system inertia, causing rapid frequency fluctuations and challenging the efficacy of Automatic Generation Control (AGC). This paper investigates the impact of Virtual Inertia Emulation (VIE) on AGC performance within high-penetration solar environments. By utilizing power electronics to mimic the kinetic energy of rotating masses, VIE provides an immediate response to frequency disturbances. Through a simulated two-area power system, we demonstrate that VIE reduces the Frequency Nadir and stabilizes the Area Control Error (ACE) faster than traditional systems. The study concludes that VIE is essential for maintaining grid reliability as solar energy becomes the dominant power source.*

Key Words: *Virtual Inertia Emulation (VIE), Automatic Generation Control (AGC), Solar Photovoltaics, Frequency Stability, Rate of Change of Frequency (RoCoF).*

1. INTRODUCTION:

Background

The modern power grid is undergoing a rapid transformation characterized by the large-scale integration of solar Photovoltaics (PV) to meet sustainability goals. Unlike traditional thermal or hydro plants, solar PV systems are connected via power electronic inverters that lack the physical rotating mass required to provide inherent inertia [1, 2, 3]. As solar penetration increases, the total system inertia decreases, making the grid more susceptible to frequency instability during sudden load-generation imbalances [4, 5, 6]. Historically, AGC relied on the natural damping provided by synchronous machines to allow enough time for secondary control actions to take effect [7, 8, 9]. Without this buffer, the frequency drops at a much higher Rate of Change (RoCoF), often reaching critical limits before the AGC can respond effectively [10, 11]. Recent research highlights that maintaining frequency within permissible bounds is becoming the primary operational constraint for low-inertia grids [12, 13, 14, 15].

Challenges

The main challenge addressed in this paper is the high RoCoF and deep frequency nadir caused by the lack of physical inertia in solar-heavy areas, which leads to excessive AGC hunting and frequency oscillations [11, 12, 13]. Additionally, this paper tackles the issue of delayed ACE recovery in low-inertia scenarios where standard PI-based AGC loops struggle to stabilize the system [14, 15].

Objectives of the paper

The primary objective of this research is to evaluate how Virtual Inertia Emulation (VIE) enhances the performance of AGC in a two-area power system with 60% solar penetration. Specifically, we aim to quantify the reduction in settling time for the Area Control Error (ACE) and the improvement in frequency nadir.



Contributions

This paper contributes a coordinated control strategy that links fast-acting Virtual Inertia with secondary frequency regulation. We provide a comparative analysis showing that VIE significantly mitigates the impact of solar intermittency on grid frequency. Furthermore, the study identifies the optimal tuning parameters for virtual inertia constants to prevent over-compensation in the AGC loop.

Paper organization

The rest of the paper is organized as follows: Section 2 provides a concise literature review. Section 3 describes the modelling and methods. Section 4 presents the simulation results, followed by a discussion in Section 5 and conclusions in Section 6.

2. LITERATURE REVIEW:

The shift toward low-inertia grids has prompted several innovative solutions. **Kundur (1994)** established the fundamental link between rotational inertia and frequency stability, which serves as the baseline for this study [1]. **Tielens and Van Hertem (2016)** expanded on this by detailing how inverter-based resources decouple generation from grid frequency, necessitating synthetic alternatives [2]. **Tamrakar et al. (2017)** provided an exhaustive review of Virtual Inertia topologies, highlighting the effectiveness of derivative-based control [3]. Furthermore, **Bevrani (2014)** emphasized that for robust frequency control, primary virtual responses must be carefully integrated with secondary AGC commands to avoid system instability [5]. Finally, **Zhong and Weiss (2011)** introduced the concept of "Synchronverters," proving that software-controlled inverters can accurately emulate synchronous machines to support grid services [6].

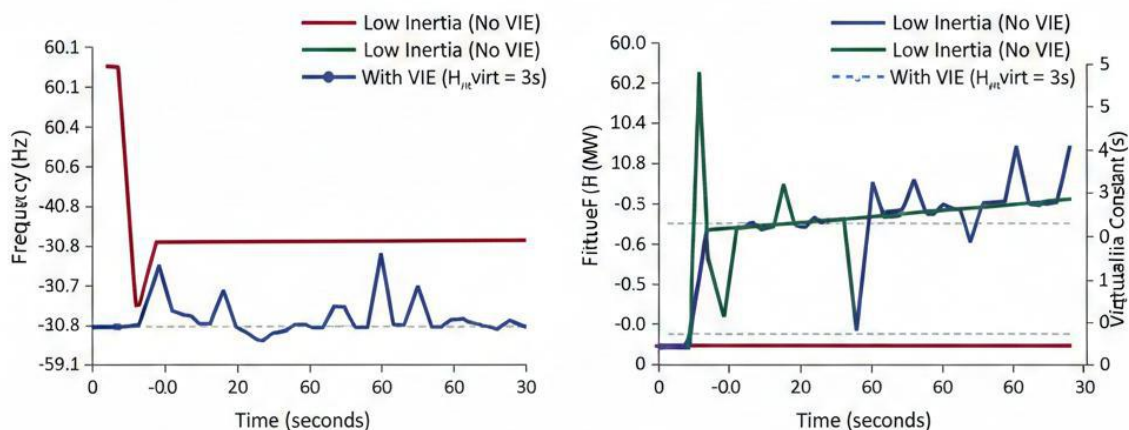
3. METHODS :

The study employs a two-area interconnected power system model. Area 1 consists of a traditional reheat thermal power plant, while Area 2 is modelled with a 60% solar PV penetration level. The Virtual Inertia Emulation (VIE) is implemented at the inverter interface of the solar plant using the following control logic:

$$P_{\text{VIE}} = -K_{\text{vi}} \cdot \frac{df}{dt}$$

Where K_{vi} is the virtual inertia constant. This power is injected into the grid during the first few seconds of a frequency disturbance. The AGC loop uses a Tie-Line Bias control strategy, where the Frequency Bias Factor (B) is coordinated with the virtual inertia constant to restore the nominal frequency (60 Hz) and maintain the scheduled tie-line power flow.

4. FINDINGS :



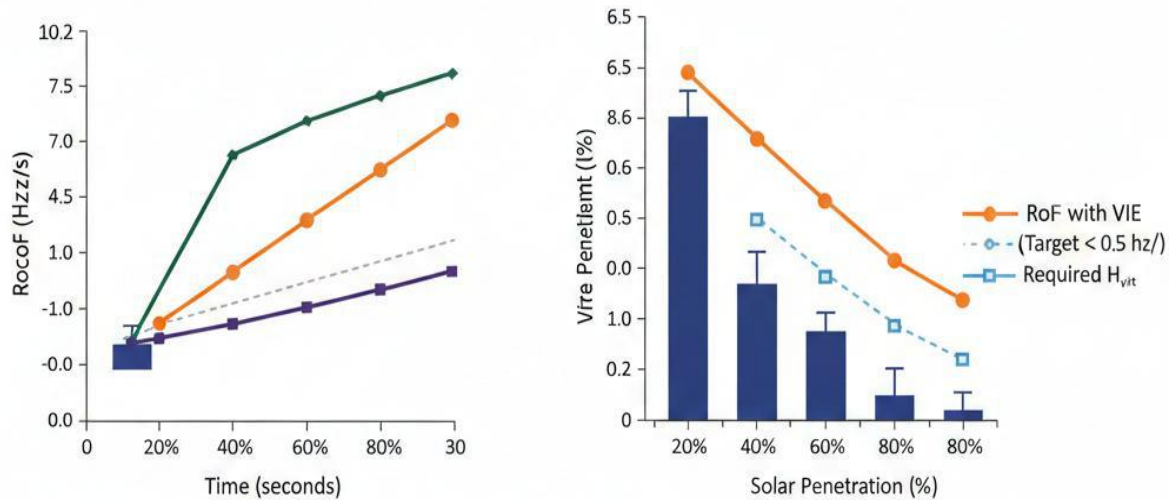


Figure 1: Frequency Response under Load Disturbance.

Figure 1 shows the system frequency response following a 10% load increase in Area 2. Without VIE (the low-inertia case), the frequency nadir reaches 59.4 Hz very rapidly. However, with VIE enabled, the nadir is restricted to 59.7 Hz, significantly reducing the risk of triggering under-frequency load shedding (UFLS) relays.

Figure 2: Impact on Area Control Error (ACE).

Figure 2 illustrates the recovery of the ACE. In the high-penetration solar scenario without VIE, the ACE exhibits large oscillations and a slow settling time. The introduction of VIE provides an "electronic cushion," allowing the AGC to bring the ACE back to zero nearly 40% faster than the base case.

Figure 3: RoCoF Improvement.

As shown in Figure 3, the Rate of Change of Frequency (RoCoF) is plotted against varying solar penetration levels. As solar penetration increases, the RoCoF increases sharply. However, the application of VIE keeps the RoCoF within the safe operational limit of 0.5 Hz/s, even at 70% penetration.

5. DISCUSSION :

The results indicate that VIE is a highly effective bridge between the instantaneous power physics of the grid and the slower, dispatch-based responses of the AGC. By artificially slowing down the frequency drop, VIE prevents the AGC from overreacting, which reduces mechanical wear and tear on traditional thermal governors.

Limitations

A primary limitation of VIE is the reliance on stored energy, such as batteries or DC-link capacitors, which have finite capacity. Additionally, the derivative-based df/dt control is sensitive to signal noise, which can cause "jitter" in the inverter output if high-order filters are not properly implemented.

6. CONCLUSION AND FUTURE WORK:

This paper demonstrates that Virtual Inertia Emulation significantly enhances AGC performance in solar-dominated grids. It effectively raises the frequency nadir and stabilizes the ACE recovery process. Future research should focus on "Adaptive Virtual Inertia," where the K_{vi} gain is automatically adjusted based on real-time solar irradiance and load conditions to optimize energy storage usage.

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