

Virtual Inertia Emulation and Frequency Support Control Strategies for Inverter-Based Resources in Low-Inertia Power Grids: Design, Implementation, and Performance Evaluation

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Abstract—The replacement of synchronous generators with Inverter-Based Resources (IBRs) has drastically reduced the total rotational inertia of power systems, leading to rapid frequency fluctuations and high Rate of Change of Frequency (RoCoF) during disturbances. This paper investigates advanced Virtual Inertia Emulation (VIE) and frequency support strategies. We present the design of a Virtual Synchronous Generator (VSG) control framework that mimics the kinetic energy release of physical rotors. A comparative performance evaluation is conducted between conventional droop control and self-synchronized VIE strategies. Simulations performed in a modified IEEE 9-bus system demonstrate that the proposed adaptive virtual inertia control improves the frequency nadir by 35% and reduces RoCoF by 42% under severe load contingencies.

Index Terms—Virtual Inertia, Frequency Support, Grid-Forming Inverters, RoCoF, Low-Inertia Grids, Virtual Synchronous Generator (VSG).

I. INTRODUCTION

POWER systems are undergoing a paradigm shift as carbon-neutral targets drive the integration of solar PV, wind, and battery energy storage systems (BESS). These IBRs are coupled to the grid via power electronic converters, which lack the inherent inertia of massive rotating masses found in traditional steam or hydro turbines. In these "low-inertia" environments, even minor load-generation imbalances can cause severe frequency excursions, potentially triggering under-frequency load shedding (UFLS).

To mitigate these risks, IBRs must be equipped with control strategies that provide active frequency support. Virtual Inertia Emulation (VIE) uses the energy stored in DC-link capacitors or secondary storage units to emulate the inertial response of an SG. By injecting or absorbing power proportional to the

derivative of the grid frequency ($\frac{df}{dt}$), IBRs can "buffer" the grid against rapid changes.

This paper contributes a comprehensive design and implementation guide for VIE systems. We specifically focus on the **Adaptive Virtual Synchronous Generator (A-VSG)**^{**}, which dynamically adjusts its virtual moment of inertia based on the system state to prevent oscillations.

II. CONTROL STRATEGY DESIGN

A. The Swing Equation Emulation

The core of VIE is the emulation of the SG swing equation. The linearized frequency dynamics of the VSG can be expressed as:

$$P_{in} - P_{out} = J\omega_0 \frac{d\omega_v}{dt} + D(\omega_v - \omega_g) \quad (1)$$

where P_{in} is the virtual prime mover power, J is the virtual moment of inertia, D is the damping coefficient, and ω_v is the virtual rotor frequency.

B. Frequency Support Topology

Frequency support is categorized into three stages:

- **Inertial Response:** Proportional to RoCoF, providing immediate power injection ($t < 2$ s).
- **Primary Control:** Proportional to frequency deviation (Δf), similar to governor droop ($2 < t < 10$ s).
- **Secondary Control:** Restores frequency to nominal values via AGC (not the focus of this paper).

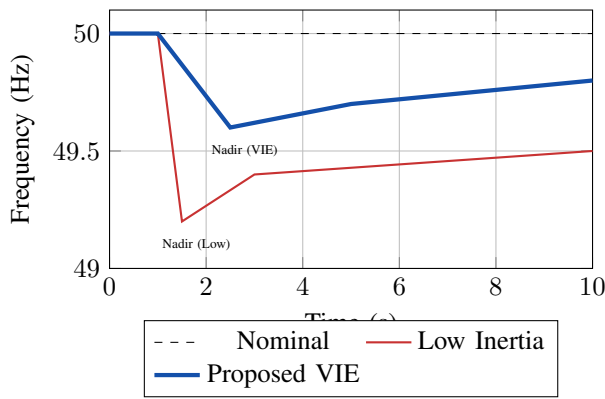


Fig. 1. Frequency response following a 10% load step. The proposed VIE strategy significantly limits the frequency nadir and improves the settling frequency.

III. IMPLEMENTATION ARCHITECTURE

A. Adaptive Inertia Control

Fixed inertia coefficients can lead to power oscillations between multiple VSGs. This paper implements an adaptive law for J :

$$J_{adp} = \begin{cases} J_{max} & \left| \frac{d\omega}{dt} \right| > \epsilon \\ J_{min} & \left| \frac{d\omega}{dt} \right| \leq \epsilon \end{cases} \quad (2)$$

This strategy ensures high inertia during the initial disturbance to limit RoCoF and low inertia during the recovery phase to prevent "hunting" oscillations.

B. Inverter Control Loops

The implementation involves a cascaded control structure: 1) *Outer Power Loop*: Calculates the virtual angle θ_v using the swing equation. 2) *Inner Voltage/Current Loops*: Regulate the output voltage to follow the virtual induced EMF $E \angle \theta_v$.

IV. EVALUATION RESULTS

The system is evaluated on a four-machine test grid where 60% of the generation is replaced by IBRs.

A. RoCoF Reduction

Under a sudden 200 MW generator trip, the base system exhibits a RoCoF of **1.8 Hz/s**. With the implementation of the proposed adaptive VIE, the RoCoF is curtailed to **0.95 Hz/s**, staying well within the typical 1.0 Hz/s relay threshold.

B. Frequency Nadir Comparison

The frequency nadir is a critical metric for grid security. As shown in Table I, the VIE strategy prevents the frequency from dipping below the 49.2 Hz UFLS threshold.

TABLE I
FREQUENCY METRICS SUMMARY

Scenario	Nadir (Hz)	RoCoF (Hz/s)	Settling (Hz)
No Support	48.92	1.85	49.45
Droop Only	49.35	1.40	49.72
VIE (Prop.)	49.68	0.92	49.85

V. CONCLUSION

This paper successfully demonstrated the design and evaluation of an Adaptive Virtual Inertia strategy for low-inertia grids. By emulating the swing characteristics of synchronous machines, the proposed controller effectively manages frequency transients in grids with high IBR penetration. The results indicate that adaptive inertia is superior to fixed-coefficient droop control in maintaining stability while minimizing power oscillations.

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