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**Comparative Analysis of Grid-forming and Grid-following Inverters on Frequency Stability in High-VRE
Power Systems**
Jonathan Firman Pardamean, Rian Fatah Mochamad, S.T., M.Eng., Ph.D.; Roni Irnawan, S.T., M.Sc., Ph.D., SMIEEE
Universitas Gadjah Mada, 2026 | Diunduh dari http://etd.repository.ugm.ac.id/

INTISARI

Integrasi sumber Energi Terbarukan Variabel (VRE) yang semakin masif ke dalam sistem tenaga listrik modern secara perlahan menggantikan generator sinkron konvensional. Transisi ini menyebabkan penurunan inersia rotasional fisik secara signifikan, sehingga membuat jaringan sangat rentan terhadap ketidakstabilan frekuensi transien. Penelitian ini bertujuan untuk mengevaluasi secara komprehensif efektivitas *Virtual Synthetic Inertia* dalam memitigasi kerentanan tersebut dengan membandingkan inverter *Grid-Following* (GFL) konvensional melawan topologi inverter *Grid-Forming* (GFM) tingkat lanjut, secara khusus arsitektur kontrol *Modified Virtual Synchronous Machine* (VSM) dan *Modified Droop*.

Simulasi dinamis dilakukan menggunakan perangkat lunak DIgSILENT PowerFactory untuk menguji ketahanan sistem. Sistem *benchmark* Kundur dimodelkan dengan tingkat penetrasi VRE sebesar 25% dan 50%, serta diberikan gangguan berupa perubahan beban secara tiba-tiba (*load step*) sebesar 5%, 10%, dan 20%. Kinerja transien dari masing-masing topologi dievaluasi secara ketat berdasarkan metrik *Frequency Nadir* dan *Rate of Change of Frequency* (RoCoF), serta diukur terhadap batas ambang keamanan operasi yaitu Nadir minimum 49,2 Hz dan batas maksimum RoCoF 1,0 Hz/s yang ditetapkan oleh *National Energy System Operator* (NESO).

Hasil simulasi menunjukkan bahwa topologi GFL mengalami degradasi kestabilan yang parah pada kondisi inersia rendah, hingga melampaui batas aman pada skenario gangguan ekstrem 20% pada penetrasi 50% dengan Nadir jatuh ke 48,88 Hz dan nilai RoCoF anjlok hingga -1,307 Hz/s. Sebaliknya, topologi GFM menunjukkan fenomena operasional yang sangat menguntungkan, ketika penetrasi VRE meningkat menjadi 50%, kestabilan frekuensi transien justru membaik berkat sintesis inersia virtual berskala masif dalam orde milidetik. Melalui injeksi daya aktif seketika, kontroler *Modified VSM* maupun *Modified Droop* terbukti berhasil menjaga kestabilan jaringan di bawah gangguan ekstrem 20% dan tetap berada dalam batas operasional yang aman. Temuan ini memvalidasi bahwa *Virtual Synthetic Inertia*, yang dihasilkan secara adaptif oleh arsitektur GFM, menawarkan solusi yang fundamental dan kokoh secara matematis untuk menjamin ketahanan transien sistem tenaga listrik masa depan yang didominasi oleh energi terbarukan.

Kata Kunci : Grid-Forming Inverter, Stabilitas Frekuensi, Virtual Synchronous Machine, Sistem Inersia Rendah, Energi Terbarukan Variabel

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ABSTRACT

The increasing integration of Variable Renewable Energy (VRE) sources into modern power systems is displacing traditional synchronous generators. This transition leads to a significant reduction in physical rotational inertia, rendering grids highly vulnerable to transient frequency instability. This research aims to comprehensively evaluate the efficacy of Virtual Synthetic Inertia in mitigating these vulnerabilities by comparing conventional Grid-Following (GFL) inverters against advanced Grid-Forming (GFM) inverter topologies, specifically the Modified Virtual Synchronous Machine (VSM) and Modified Droop control architectures.

Dynamic simulations were conducted using DIgSILENT PowerFactory to assess system robustness. The Kundur two-area benchmark system was modeled with VRE penetration levels of 25% and 50% and subjected to varying magnitudes of load step disturbances (5%, 10%, and 20%). The transient performance of each topology was rigorously evaluated based on the Frequency Nadir and the Rate of Change of Frequency (RoCoF), measuring them against the strict safety thresholds of a minimum 49.2 Hz Nadir and a maximum 1.0 Hz/s RoCoF magnitude defined by the National Energy System Operator (NESO).

The simulation results reveal that GFL topologies suffer severe degradation under low-inertia conditions, completely failing the safety limits during a 20% extreme load step at 50% penetration with a Nadir dropping to 48.88 Hz and a critical RoCoF plunge to -1.307 Hz/s. Conversely, GFM topologies exhibit a highly favorable phenomenon, as VRE penetration increases to 50%, the transient frequency stability improves due to the massive, millisecond-level synthesis of virtual inertia. Through instantaneous active power injection, both Modified VSM and Modified Droop controllers successfully maintained grid stability under extreme 20% disturbances while remaining well within safe operational limits. The findings validate that Virtual Synthetic Inertia, generated by dynamically adaptive GFM architectures, offers a fundamental and mathematically robust solution for ensuring the transient resilience of future highly-renewable power systems.

Keywords : Grid-Forming Inverter, Frequency Stability, Virtual Synchronous Machine, Low-Inertia Systems, Variable Renewable Energy