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Dynamic Modeling and Analysis of Virtual Synchronous Generator Based Grid Forming Inverter in HIL
Rizal Kurniawan Saputra, Ir. Husni Rois Ali, S.T., M.Eng., Ph.D., DIC., SMIEEE.; Dr.-Ing. Ir. Yohan Fajar Sidik, S.T., M
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INTISARI

Intensitas emisi CO_2 global dari sektor energi listrik diperkirakan menurun hingga tahun 2027, didorong oleh tingginya penetrasi energi terbarukan yang mengubah pembangkitan dari semula didominasi generator sinkron menjadi didominasi *inverter-based resources* (IBR). Transisi ini mengurangi inersia sistem dan menantang stabilitas dinamis sistem tenaga. *Grid-Forming Inverter* (GFM) berbasis kendali *Virtual Synchronous Generator* (VSG) menawarkan solusi dengan kemampuan membentuk tegangan dan frekuensi secara mandiri serta memberikan dukungan inersia pada sistem. Penelitian ini mengembangkan model dinamis GFM berbasis kendali VSG dalam kerangka dq yang mencakup kendali *outer loops*, kendali *inner loops*, serta topologi jaringan inverter, dan mengimplementasikannya pada pengujian *Hardware-in-the-Loop* (HIL). Model mula-mula dibangun di MATLAB/Simulink, kemudian dibangun ulang pada PLECS agar sesuai dengan lingkungan pengujian HIL menggunakan RT Box 2, dengan konfigurasi *multi-core* (3 CPU) dan *discretization step size* 9 mikrodetik per *core*. Performa GFM dianalisis melalui pengujian *steady state response* dan *dynamic response* pada kondisi *very weak grid* dan *strong grid*. Hasil menunjukkan bahwa GFM berperforma lebih baik pada kondisi *very weak grid* dibandingkan *strong grid*, yang ditandai dengan lebih tingginya arus transien dan *coupling* daya aktif-reaktif pada kondisi *strong grid*. Penerapan *virtual impedance loop* terbukti efektif membatasi arus transien, mengurangi *coupling* daya aktif-reaktif, serta mempertahankan stabilitas sistem pada kondisi *strong grid*, yang tanpanya inverter memasuki kondisi tidak stabil. Pengujian HIL secara *real-time* menunjukkan bahwa strategi kontrol GFM yang dikembangkan, dengan penerapan *virtual impedance loop*, mampu menjaga stabilitas sistem secara keseluruhan pada kondisi *very weak grid* maupun *strong grid*, sehingga memberikan dasar praktis bagi penerapan perangkat keras (*hardware deployment*) teknologi GFM dalam sistem energi terbarukan di masa mendatang.

Kata kunci: Stabilitas Sistem Tenaga Listrik, *Grid-Forming Inverter*, *Virtual Synchronous Generator*, *Hardware-in-the-Loop*, RT Box 2

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ABSTRACT

The global CO_2 emission intensity from the electric power sector is projected to decline through 2027, driven by the high penetration of renewable energy that shifts generation from synchronous generators toward inverter-based resources (IBR). This transition reduces system inertia and challenges the dynamic stability of the power system. Grid-Forming Inverter (GFM) based on Virtual Synchronous Generator (VSG) control offers a solution through its ability to independently establish voltage and frequency while providing inertia support to the system. This research develops a dynamic model of a VSG-based GFM in the dq reference frame, covering the outer loops, inner loops, and inverter network topology, and implements it in Hardware-in-the-Loop (HIL) testing. The model is first built in MATLAB/Simulink and then rebuilt in PLECS to suit the HIL environment on RT Box 2, using a multi-core configuration (3 CPUs) with a discretization step size of 9 microseconds per core. GFM performance is analyzed through steady state and dynamic response testing under very weak grid and strong grid conditions. The results show that the GFM performs better under very weak grid conditions than under strong grid conditions, as indicated by the higher transient current and active-reactive power coupling observed under the strong grid. Applying a virtual impedance loop effectively limits the transient current, reduces the power coupling, and maintains system stability under strong grid conditions, without which the inverter enters an unstable operating regime. Real-time HIL testing shows that the developed GFM control strategy, when equipped with the virtual impedance loop, maintains overall system stability under both very weak grid and strong grid conditions, providing a practical basis for the future hardware deployment of GFM technology in renewable energy systems.

Keywords: Power System Stability, Grid-Forming Inverter, Virtual Synchronous Generator, Hardware-in-the-Loop, RT Box 2