ABSTRAK

Peningkatan penetrasi pembangkit *photovoltaic* (PV) berbasis inverter dalam sistem tenaga listrik modern menimbulkan tantangan terhadap stabilitas transien akibat berkurangnya kontribusi inersia mekanik dari generator sinkron konvensional. Kondisi ini relevan dengan target bauran energi terbarukan Indonesia sebesar 51,6% pada tahun 2044 dan komitmen *Net Zero Emission* 2060.

Penelitian ini mengkaji stabilitas transien sistem *Single Machine Infinite Bus* (SMIB) dengan integrasi PV menggunakan dua strategi kontrol inverter, yaitu *Grid-following* (GFL) dan *Grid-Forming* (GFM). Sistem GFL dianalisis menggunakan DIgSILENT PowerFactory dengan mempertimbangkan variasi penetrasi PV, lokasi gangguan, dan parameter *Phase-Locked Loop* (PLL), sedangkan sistem GFM dianalisis menggunakan MATLAB/Simulink dengan pendekatan *Virtual Synchronous Generator* (VSG) melalui variasi inersia virtual (J) dan koefisien *damping* (D_p). Nilai *Critical Clearing Time* (CCT) sebagai indikator utama stabilitas transien ditentukan menggunakan algoritma numeris *bisection*.

Hasil penelitian menunjukkan bahwa peningkatan penetrasi PV berbasis GFL menyebabkan penurunan CCT dari 260 ms pada kondisi tanpa PV menjadi 141 ms pada penetrasi 90%, dengan laju penurunan yang semakin cepat pada penetrasi di atas 50%. Lokasi gangguan terbukti lebih dominan mempengaruhi nilai CCT dibandingkan tingkat penetrasi PV, di mana gangguan pada posisi 80% Line 2 menghasilkan CCT hingga 1.205 ms pada penetrasi PV 50%. Peningkatan *gain* proporsional (K_p) PLL yang berlebihan menurunkan nilai CCT dan memperbesar amplitudo osilasi sudut rotor, sedangkan variasi *gain* integral (K_i) tidak berpengaruh signifikan terhadap respon transien. Pada sistem GFM, inersia virtual memberikan pengaruh dominan terhadap nilai CCT yang meningkat dari 1,104 s pada J = 250 menjadi 1,734 s pada J = 750, sedangkan koefisien *damping* lebih berpengaruh terhadap kualitas pemulihan sistem pasca gangguan. Sistem GFL dan GFM menunjukkan karakteristik stabilitas transien yang berbeda, CCT sistem GFL menurun seiring meningkatnya penetrasi PV, sedangkan sistem GFM mampu mempertahankan nilai CCT yang tinggi melalui pengaturan inersia virtual dan koefisien *damping*.

Kata kunci— *Critical Clearing Time, SMIB, Grid-Following, Grid-Forming, Stabilitas Transien, Photovoltaic, VSG.*

ABSTRACT

The increasing penetration of inverter-based renewable energy generation, particularly photovoltaic (PV), in modern power systems poses challenges to transient stability due to the reduced contribution of mechanical inertia from conventional synchronous generators. This condition is relevant to Indonesia's target of 51.6% renewable energy mix by 2044 and its commitment to Net Zero Emission by 2060.

This study investigates the transient stability of a Single Machine Infinite Bus (SMIB) system integrated with PV generation using two inverter control strategies, namely Grid-following (GFL) and Grid-Forming (GFM). The GFL system was analyzed using DIgSILENT PowerFactory considering variations in PV penetration levels, fault locations, and Phase-Locked Loop (PLL) control parameters, while the GFM system was analyzed using MATLAB/Simulink with a Virtual Synchronous Generator (VSG) approach through variations in virtual inertia (J) and damping coefficient (D_p). The Critical Clearing Time (CCT) was used as the primary transient stability indicator and determined using a numerical bisection algorithm for both systems.

The results show that increasing GFL-based PV penetration reduces CCT from 260 ms at zero PV penetration to 141 ms at 90% penetration, with the rate of decline accelerating significantly above 50% penetration. Fault location proved more dominant in influencing CCT than the PV penetration level, where a fault at 80% of Line 2 yielded a CCT of up to 1,205 ms at 50% PV penetration, demonstrating that under certain fault locations, higher PV penetration can actually improve transient stability. Excessive increase in PLL proportional gain (K_p) reduced CCT and increased rotor angle oscillation amplitude, while variations in integral gain (K_i) showed no significant effect on transient response. In the GFM system, virtual inertia had a dominant influence on CCT, which increased from 1.104 s at J = 250 to 1.734 s at J = 750, while the damping coefficient primarily affected the quality of post-fault recovery. The GFL and GFM systems exhibited distinct transient stability characteristics the GFL system showed declining CCT with increasing PV penetration, while the GFM system maintained high CCT values through virtual inertia and damping adjustment

Keywords— Critical Clearing Time, SMIB, Grid-Following, Grid-Forming, Transient Stability, Photovoltaic, VSG.