ABSTRAK

Sistem dengan topologi radial dan keterbatasan interkoneksi, seperti Subsistem Aceh, memiliki kerentanan terhadap stabilitas frekuensi pascagangguan, terutama akibat lepasnya pembangkit maupun terputusnya saluran transmisi. Penelitian ini bertujuan untuk mengoptimasi lokasi dan kapasitas *Battery Energy Storage System* (BESS) guna meningkatkan stabilitas frekuensi menggunakan *Bat Algorithm* (BAT). Proses optimasi menggunakan fungsi objektif hibrida yang mempertimbangkan efisiensi kapasitas BESS dan indikator stabilitas frekuensi, meliputi *Rate of Change of Frequency* (RoCoF) pada jendela 200 ms, *frequency nadir*, *settling time*, dan *Integral Absolute Frequency Deviation* (IAFD).

Simulasi dilakukan melalui arsitektur *co-simulation* antara Python dan DIgSILENT PowerFactory. BESS dimodelkan menggunakan *Simplified Model* berbasis *droop control* untuk memberikan dukungan *Fast Frequency Response* (FFR). Model divalidasi menggunakan sistem IEEE 9-bus melalui perbandingan RoCoF hasil simulasi terhadap perhitungan analitik berbasis *swing equation*, serta validasi respons daya aktif BESS terhadap karakteristik *droop control*. Selanjutnya, sensitivitas solusi dievaluasi melalui uji sensitivitas lintas skenario terhadap tiga mode kontingensi, yaitu *generator trip* (GEN_TRIP), *maintenance and line trip* (MLT), serta *maintenance and double line trip* (MDLT).

Hasil optimasi pada titik operasi WBP dan skenario utama GEN_TRIP menunjukkan bahwa BESS berkapasitas 46,5 MW di GI 150 kV Nagan Raya merupakan solusi terbaik untuk meningkatkan stabilitas frekuensi tanpa melanggar batas operasi. Solusi ini meningkatkan *frequency nadir* menjadi sekitar 49,8226 Hz, memperbaiki RoCoF menjadi sekitar -0,5352 Hz/s, menurunkan IAFD menjadi sekitar 0,5043 Hz·s, dan menghasilkan *settling time* sekitar 7,9117 detik. Hasil uji sensitivitas menunjukkan bahwa BESS masih efektif menjaga sistem dalam batas operasi pada skenario GEN_TRIP dan MLT. Skenario MDLT digunakan sebagai *stress test* ekstrem untuk mengidentifikasi batas efektivitas BESS tunggal, bukan sebagai rekomendasi operasi normal Subsistem Aceh secara terisolasi. Perluasan ruang pencarian hingga 500 MW mampu memperbaiki indikator frekuensi, tetapi belum memenuhi seluruh batas operasi akibat perubahan topologi, hilangnya dukungan interkoneksi, dan pembebanan peralatan. Penelitian ini menyimpulkan bahwa BESS efektif sebagai dukungan respons transien pada kontingensi ringan hingga menengah, sedangkan kontingensi ekstrem memerlukan strategi mitigasi hibrida. Kapasitas BESS yang diperoleh merupakan kapasitas daya teknis pada titik operasi dan skenario yang dimodelkan, sehingga tidak dapat langsung diinterpretasikan sebagai kebutuhan energi jangka panjang atau rekomendasi investasi.

Kata Kunci: *Battery Energy Storage System*, Stabilitas Frekuensi, *Bat Algorithm*, RoCoF, *Frequency Nadir*, *Settling Time*, IAFD, Uji Sensitivitas, Subsistem Aceh.

ABSTRACT

Power systems with radial topologies and limited interconnections, such as the Aceh Subsystem, are vulnerable to post-disturbance frequency instability caused by generator trips or transmission line outages. This study aims to optimize the location and capacity of a Battery Energy Storage System (BESS) to enhance frequency stability using the Bat Algorithm (BAT). The optimization employs a hybrid objective function that considers BESS sizing efficiency and frequency stability indicators, including the Rate of Change of Frequency (RoCoF) within a 200 ms window, frequency nadir, settling time, and Integral Absolute Frequency Deviation (IAFD).

The simulations were conducted using a co-simulation architecture between Python and DIgSILENT PowerFactory. The BESS was modeled using a Simplified Model based on droop control to provide Fast Frequency Response (FFR) support. The model was validated using the IEEE 9-bus system by comparing the simulated RoCoF with analytical calculations based on the swing equation, as well as by validating the BESS active power response against the droop control characteristic. The robustness of the solution was then evaluated through cross-scenario sensitivity analysis under three contingency modes: generator trip (GEN_TRIP), maintenance and line trip (MLT), and maintenance and double line trip (MDLT).

The optimization results for the WBP operating point and the main GEN_TRIP scenario show that a 46.5 MW BESS at the Nagan Raya 150 kV Substation is the best solution for improving frequency stability without violating operational limits. The solution increases the frequency nadir to approximately 49.8226 Hz, improves RoCoF to approximately -0.5352 Hz/s, reduces IAFD to approximately 0.5043 Hz·s, and achieves a settling time of approximately 7.9117 s. The sensitivity analysis indicates that the BESS remains effective in maintaining the system within operational limits under the GEN_TRIP and MLT scenarios. The MDLT scenario is used as an extreme stress test to identify the effectiveness boundary of a single BESS, rather than as a recommendation for normal isolated operation of the Aceh Subsystem. Expanding the capacity search range up to 500 MW improves the frequency indicators but does not satisfy all operational limits because of topology changes, the loss of interconnection support, and equipment loading. This study concludes that BESS is effective as a transient-response support measure under mild-to-moderate contingencies, whereas extreme contingencies require a hybrid mitigation strategy. The resulting BESS capacity represents a technical power rating for the modeled operating point and scenario and should not be directly interpreted as a long-term energy requirement or an investment recommendation.

Keywords: Battery Energy Storage System, Frequency Stability, Bat Algorithm, RoCoF, Frequency Nadir, Settling Time, IAFD, Sensitivity Analysis, Aceh Subsystem.