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Performance placement of BESS in the Sulawesi-Southern interconnected power system

Zaenab Muslimin[1], Indar Chaerah Gunadin[1], Fitriyanti Mayasari[1], Muhira Dzar Faraby[2] Asma Amaliah[3], Isminarti[4]
[1]Department of Electrical Engineering, Faculty of Engineering, Universitas Hasanuddin, Makassar, Indonesia
[2]Department of Electrical Engineering, Politeknik Negeri Ujung Pandang, Makassar, Indonesia
[3]Department of Telecomminucation Engineering, Politeknik Negeri Ujung Pandang, Makassar, Indonesia
[4]Department of Mechatronic Engineering, Politeknik Bosowa, Makassar, Indonesia

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ABSTRACT

Frequency regulation and active power loss management are crucial aspects of power system operations. Battery energy storage systems (BESS) have emerged as an innovative solution to enhance grid performance, especially in addressing frequency fluctuations and reducing power losses. This study explores the role of BESS in optimizing frequency regulation and managing active power losses in the power system through several BESS integration scenarios. In this study, a BESS with a capacity of 8.437 MW was used and analyzed using symmetric steady-state simulations in DigSILENT PowerFactory software. The simulations aim to test the effectiveness of BESS in frequency regulation and minimizing active power losses in the Sulbagsel system. The analysis results show that implementing BESS can respond effectively to both over-frequency and under-frequency conditions in the Sulbagsel system. In the discharge scenario, BESS can reduce the system's average frequency by 0.02 Hz and decrease active power losses by up to 1.09 MW. Conversely, in the charge scenario, active power losses increase by 1.22 MW when the BESS is installed on Bus Tonasa. This study provides valuable insights for developing BESS-based frequency regulation strategies that contribute to the stability and efficiency of the power system.

Corresponding Author:

Zaenab Muslimin
Department of Electrical Engineering, Faculty of Engineering, Universitas Hasanuddin
Perintis Kemerdekaan St. Km. 10, Makassar 90222, Indonesia
Email: zaenab@unhas.ac.id

1. INTRODUCTION

With growing concerns about environmental pollution and the energy crisis, along with the need for a low-carbon transition, the development and utilization of renewable energy sources (RES) have become increasingly important to ensure a clean and sustainable energy supply [1]. The interconnected power system of Southern Sulawesi (Sulbagsel), Indonesia, has expanded its capacity to meet the high energy demands of the smelting industry, which requires stable and sustainable energy for processing mined materials [2]. Through an integrated "source-grid-load-storage" regulation, energy storage systems are optimally used to increase RES consumption, ensuring reliable network operations [3].

The BESS is a device that converts chemical energy into electrical energy and vice versa, with energy capacity as a primary classification aspect [4]. The capacity of a BESS depends on the number and size of installed cells and is measured in ampere-hours (Ah), indicating how much current can be supplied or absorbed in one hour [5]. BESS is designed for high durability, with modified chemicals for long-term use

[6]. Chemical energy is stored in an internal solution until needed, whereupon the BESS converts it back into electrical energy to power various electrical devices [7]. The BESS control system is designed to manage battery-based energy storage operations, aiming to optimize energy use, improve efficiency, and provide services that support grid balance and reliability [8]. BESS plays a crucial role in this transition by enhancing flexibility, maintaining frequency stability, and minimizing power losses. While the present study focuses on the Sulbagsel interconnected system, the challenges addressed, such as frequency instability due to load variations and high renewable penetration, as well as active power losses in heavily loaded buses, are also common in many islanded and weakly interconnected grids worldwide. Therefore, insights gained from this case study can be extrapolated to other regional power systems facing similar operational constraints, particularly in Southeast Asia and other developing regions with growing renewable shares.

To enable BESS to serve multiple functions, its size must be appropriately scaled to meet required capabilities [9]. Literature presents extensive research on BESS sizing for single applications such as voltage deviation mitigation, power loss reduction, frequency regulation, inertia support, and peak shaving [10]-[12], while studies on BESS sizing for value-stacking applications remain limited [13], [14]. A study [15] explored BESS sizing specifically for inertia response and primary frequency reserve, estimating BESS capacity based on grid unit inertia contributions. However, their method yields only an estimated, rather than optimal, BESS size. The study [16] introduced a methodology for determining BESS sizing using the Fourier series, targeting capacity assessment for value-stacking applications like reducing power losses and mitigating voltage deviations. The works in [17] explain that BESS supports applications such as power smoothing, reverse power flow management, and state-of-charge balancing, while [18] discusses BESS roles in peak shaving, load leveling, and controlling voltage rises. Importantly, these studies do not cover BESS sizing for multifunctional use but rather focus on control strategies for various BESS applications. According to existing literature on BESS sizing for value-stacking purposes, no research thus far has explored sizing BESS for multiple roles like frequency regulation, minimizing power losses, and managing voltage deviations [19]-[21].

Frequency instability due to load changes reduces power quality [22]. Data from PT. PLN PERSERO indicates that increasing load demand and intermittent generation, especially in the Sulbagsel system, impact frequency stability [23]-[24]. BESS is now more widely implemented, even rented, to reduce operational costs and help maintain frequency stability. BESS serves to improve power quality, particularly during frequency disturbances when the system frequency deviates from the nominal range of 50 Hz [25], [26].

This study aims to analyze the performance of BESS placement and sizing in the Sulbagsel system through simulations using DigSILENT Power Factory 15.1. The BESS storage capacity is determined through a calculation method based on statistically analyzed historical frequency data, optimizing its function as a frequency regulator. Before calculating the capacity of the BESS, it is essential to know the system strength index (SSI), also known as frequency gain or stiffness, for the Sulbagsel power system in 2022. The novelty of this study lies in the application of an SSI-based sizing approach integrated with active power loss analysis for BESS placement. Unlike many previous studies that focus on single-objective applications or rely solely on complex metaheuristic optimization, this work demonstrates how SSI can be practically employed to size BESS for frequency regulation and simultaneously evaluate placement impacts on system losses. By explicitly combining SSI-based sizing with loss-based placement evaluation, this study contributes a methodological perspective that balances analytical rigor with practical feasibility [6], [8], [10], [15]. SSI indicates the system's ability to provide power in case of a major generation trip or a power supply loss. If the power loss exceeds the SSI, the system frequency will drop below 49.0 Hz, affecting system stability. It is important to note that the governor will only respond after 5 seconds. BESS placement can be implemented at several locations, such as at a transmission substation, at a distribution substation near the load center, or collocated with a generator/variable renewable energy (VRE) source. This research is expected to provide recommendations for the relevant companies to enhance energy reliability through the integration of renewable energy and achieve optimal efficiency in the operation of the Sulbagsel system. This paper is organized as follows: i) Section 2 is the methodology that is divided into five parts: first is the Sulbagsel Interconnection Electrical System, second is the capacity of BESS, third is the placement of BESS, fourth is the case study, and fifth is the step of the research; ii) Section 3 presents the result; and iii) Last section 4 is conclusion.

2. METODOLOGY

2.1. Sulbagsel interconnection electrical system

The Sulbagsel system is the electrical power system located in the southern part of Sulawesi Island, Indonesia. This system covers areas in South Sulawesi Province, West Sulawesi Province, Southeast Sulawesi Province, and half of Central Sulawesi Province [27]. Figure 1 shows the single-line diagram of the Sulbagsel system, consisting of 30 kV, 70 kV, 150 kV, and 275 kV buses. Each bus is interconnected through transmission lines and transformers, with transformers linking buses of different voltage levels. The generation units in the diagram include various types, both conventional power plants and those classified as renewable energy sources.

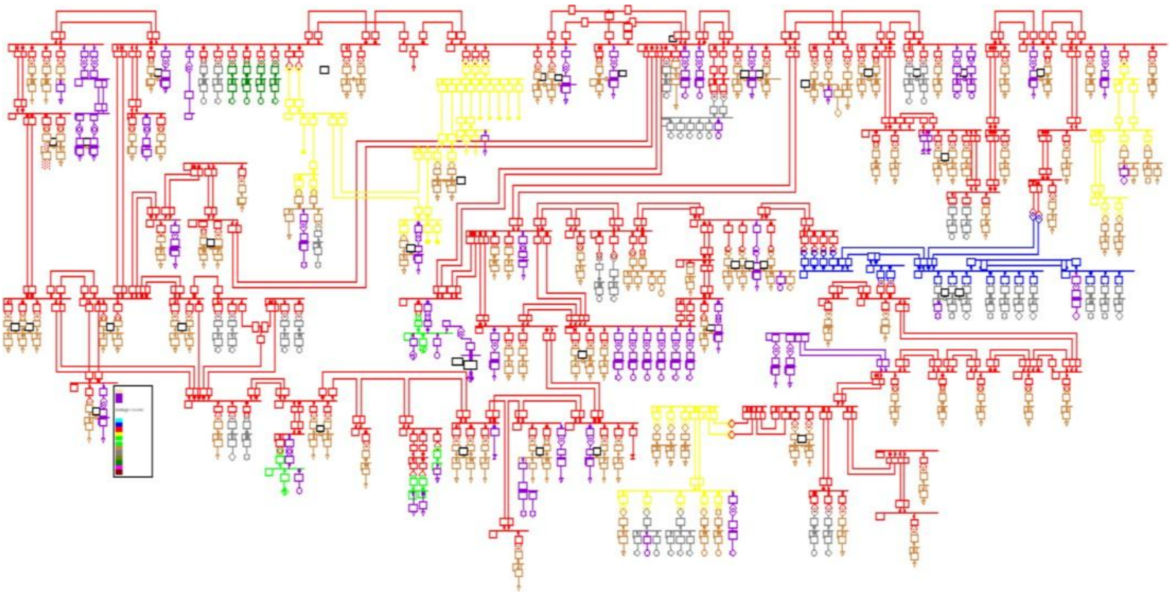

Figure 1. Single line diagram of Sulbagsel system [27]

2.2. Capacity of BESS
2.2.1. System strength index (SSI)

The system strength index is obtained from simulation results with scenarios of disconnecting several variations of generators in the Sulbagsel power system [28], as shown in Table 1. Table 1 shows the frequency deviations of several generators during a simulation of generator disconnection from the Sulbagsel system to obtain the Sulbagsel system strength index, which is used to determine BESS capacity during frequency disturbances. Based on the Δf and ΔP data in Table 1, the system strength index (SSI) is obtained using linear regression. The linear regression results based on Table 1 yield an SSI of 375.77 MW/Hz.

Table 1. Scenario simulation of power plant release

No	Power plant	ΔP [MW]	Basic frequency (Hz)	Disturbance frequency (Hz)	Δf [Hz]
1	PLTU JENEPONTO 1	100.5	50	49.739	0.261
2	PLTU JENEPONTO 2	92.8	50	49.761	0.239
3	PLTU PUNAGAYA 1	86.7	50	49.785	0.215
4	PLTU PUNAGAYA 2	84.7	50	49.805	0.195
5	PLTA BAKARU 1	53.5	50	49.871	0.129
6	PLTA BAKARU 2	50.1	50	49.882	0.118
7	PLTA POSO 2A 3	48.7	50	49.888	0.112
8	PLTU BARRU	43.1	50	49.951	0.049
9	PLTA POSO 2A 2	47.4	50	49.893	0.107
10	PLTU MORAMO 2	43.2	50	49.907	0.093
11	PLTA POSO 2B 4	42.7	50	49.901	0.099
12	PLTU MORAMO 1	42.3	50	49.904	0.096
13	PLTA MALEA 2	38.7	50	49.927	0.089
14	PLTD TELLO	23.8	50	49.951	0.079
15	POSO 1 #3	25.5	50	49.906	0.094
16	POSO 1#2	22.7	50	49.909	0.091
17	PLTA BILI-BILI 2	6.8	50	49.990	0.01
18	PLTD SILAE 2	8.7	50	49.984	0.016
19	TONASA 6	7.6	50	49.975	0.025

2.2.2. Capacity of BESS

The BESS capacity is calculated using monthly frequency data to analyze the characteristics of system frequency changes over one year. Figures 2 and 3 present frequency histograms for 12 months based on real PT. PLN (Persero) data from 2022, covering both under-frequency and over-frequency conditions

[28]. The SSI value obtained from the simulation is then multiplied by the frequency deviation beyond system limits and by the droop value to determine the required BESS capacity, as expressed in (1):

$$BESS\ Capacity\ \left[\frac{MW}{Hz}\right] = SSI * GD\ [\%] * \Delta f\ [Hz] \quad (1)$$

where GD is governor droop in this case 5% and Δf is the change of frequency. The value of 1 is obtained from equation 1 as 8.437 MW.

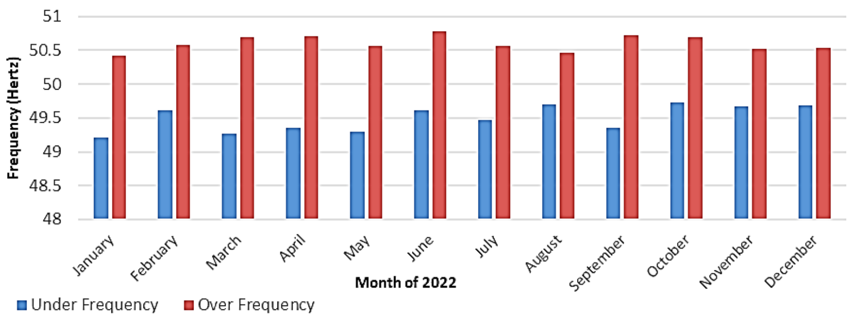

Figure 2. Average frequency during under-frequency and over-frequency disturbances

2.3. Placement of BESS

The location of BESS significantly influences the services it can offer, with optimal placement depending on specific use case needs [29]. For instance, BESS at substations can provide various services, support transmission issues, replace or defer peak capacity investments, and facilitate frequency regulation without placement constraints due to its global parameter nature [30]. In the context of frequency regulation, the placement of BESS is not a constraint because the system frequency is uniform across the interconnected system, including the load, generation, transmission, and distribution sides, allowing for placement anywhere as long as there is sufficient space in the substation for the BESS [31]. The BESS for frequency regulation in the Sulbagsel system is placed alongside the generator or variable renewable energy (VRE) and, in this study, is integrated with the Sidrap wind power plant (PLTB Sidrap). The placement of BESS to reduce active power losses will be positioned at bus locations with the highest active power losses and also at buses with the largest loads [32].

2.4. Case study

To analyze the performance of BESS placement in the Sulbagsel interconnected system, several simulations were conducted. These case studies aimed to evaluate different placement strategies and their impact on system efficiency. The results will provide insights into the optimal locations for BESS to enhance overall system performance. The simulation was conducted by examining two key aspects: frequency regulation and active power loss. The simulation scenarios carried out in this research are;

- Simulation during load shedding at the Tonasa bus before and after the addition of a battery energy storage system (BESS).
- Simulation during the load shedding of the Tolo wind power plant (PLTB) before and after the addition of a battery energy storage system (BESS).
- Simulation of power losses in the Sulbagsel electrical system before and after the addition of a battery energy storage system (BESS).

2.5. Steps of the research

The methodological framework of this study ensures a systematic and transparent process for BESS sizing and placement. It begins with collecting grid data—load profiles, network topology, and generator characteristics, which form the basis of the simulation model. The system strength index (SSI) is then calculated to estimate the required BESS capacity, followed by identifying candidate placement options at high-load buses and renewable integration points. These options are tested in PowerFactory through load shedding and generator outage scenarios, and the results are evaluated using key performance indicators such as frequency stability, loss reduction, and system efficiency. The optimal BESS placement is finally selected based on comparative performance, providing practical insights for improving grid reliability. Here are the step-by-step points of the research.

1) Start: Initialize the BESS placement analysis process.
2) Input grid data: Collect system data, including load profiles, network topology, and generator characteristics.
3) Compute SSI: Calculate the system strength index (SSI) based on generator disconnection scenarios to assess system strength.
4) Determine BESS capacity: Define the required BESS capacity using SSI values and observed frequency deviations.
5) Identify candidate placement options: Select potential BESS locations, such as high-load buses or variable renewable energy (VRE) sites.
6) Simulate scenarios in PowerFactory: Run simulations in PowerFactory, including load shedding, generator outages, and power flow cases.
7) Evaluate performance metrics: Assess simulation outcomes using performance metrics such as frequency stability, loss reduction, and efficiency.
8) Select optimal BESS placement: Choose the most suitable BESS location based on the performance evaluation.
9) End: Conclude the process after determining the optimal BESS sizing and placement.

3. RESULTS

The simulation results presented in this study are based on a Sulbagsel grid model that incorporates detailed system parameters. Load profiles were derived from PLN operational data for 2022, reflecting typical daily and seasonal variations. The grid topology includes transmission voltage levels of 30 kV, 70 kV, 150 kV, and 275 kV, with interconnections represented according to the official single-line diagram. For the BESS, a capacity of 8.437 MW was adopted based on the SSI calculation, with inverter ratings of 10 MVA and a dispatch logic designed for both charging during over-frequency events and discharging during under-frequency events. These explicit assumptions provide the technical foundation for the frequency response and power loss results, ensuring that the analysis is reproducible and transparent.

3.1. Load shedding of the Tonasa bus

The Sulbagsel power system must consistently meet its consumers' electricity demands. Therefore, the power generated by the system must match the electricity load requirements. If the generated power exceeds the load demand, the frequency will increase. Maintaining a balance between power supply and demand is crucial to keep the system stable. A frequency quality simulation for the Sulbagsel power system is carried out by shedding the Tonasa load, one of the largest-capacity loads in the Sulbagsel interconnection system. This scenario aims to assess the BESS's response under over-frequency or excess frequency disturbances. The simulation result can be seen in Figure 3.

In Figures 3(a)-3(d), the X-axis is time in seconds, and the Y-axis is frequency in hertz for Figures 3(a) and 3(b), and power in MW for Figures 3(c) and 3(d). Figure 3(a) shows the frequency at Pamona (275 kV), Bakaru (150 kV), Tello (70 kV), and Panakukang (20 kV) buses after simulating an 86.7 MW Tonasa load shedding scenario without BESS. The 100-second simulation begins with load shedding at 10 seconds, maintaining a stable frequency of 50 Hz initially. At 12 seconds, the frequency rises to 50.143 Hz due to excess generation, but it gradually returns to near 50 Hz as governors adjust output power, causing minor oscillations while stabilizing the frequency. Figure 3(b) shows the frequency at the Pamona bus (275 kV), Bakaru bus (150 kV), Tello bus (70 kV), and Panakukang bus (20 kV) after simulating the Tonasa load shedding of 86.7 MW with an 8.437 MW battery energy storage system (BESS).

The 100-second simulation begins with the load shedding at the 10-second mark, where the battery starts charging the Sulbagsel system with 6.870 MW. Frequency remains stable at 50 Hz from 0 to 10 seconds, then drops to 50.128 Hz at 12 seconds due to the battery's rapid response. After this drop, the frequency further decreases towards 50 Hz from 15 to 50 seconds as generator governors reduce output power to regain equilibrium, leading to oscillations from an imbalance between load and generation. From Figure 3(c), the simulation shows that shedding the Tonasa load increases the system frequency to 50.143 Hz. In contrast, with the 8.437 MW BESS installed, the frequency drops to 50.128 Hz by charging 6.870 MW into the system, demonstrating the frequency change before the BESS installation. After the Tonasa load shedding, frequency oscillations lead other integrated generators to experience generation fluctuations, as shown in Figure 3(d). At 11 seconds, some generators reduce output power in response to a governor signal indicating a rise in frequency, aiming to stabilize it around 50 Hz. The graph shows that the system undergoes frequency oscillations due to significant load shedding, resulting in insufficient stability

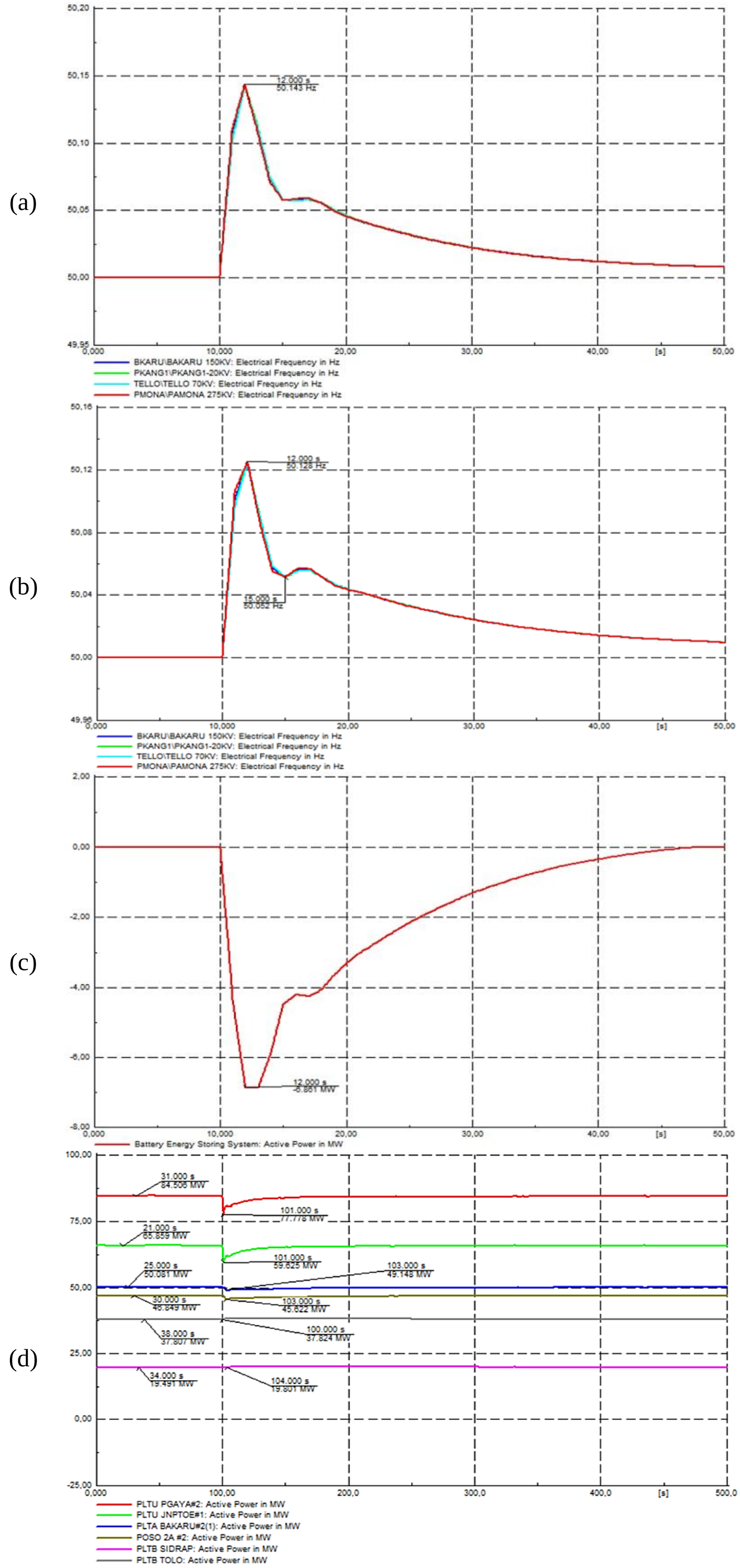

Figure 3. Tonasa load shedding simulation results: (a) frequency response without BESS, (b) frequency response with BESS, (c) power response without BESS, and (d) power response with BESS

3.2. Generator shedding of PLTB Tolo

If the generated power is less than the load demand, the frequency will decrease. The simulation scenario of shedding the Tolo wind power plant aims to observe the condition of the battery energy storage system (BESS) during under-frequency conditions, as shown in Figure 4.

In Figures 4(a)-4(d), the X-axis is time in seconds, and the Y-axis is frequency in hertz for Figures 4(a) and 4(b), and power in MW for 4(c) and 4(d). Figure 4(a) displays the frequency graph at the Pamona bus (275 kV), Bakaru bus (150 kV), Tello bus (70 kV), and Panakukang bus (20 kV) after simulating the 37.8 MW load shedding scenario of the Tolo wind power plant before installing the BESS. The simulation runs for 100 seconds, with the shedding executed at the 100-second mark. The results show the frequency remains stable at 50 Hz from 0 to 10 seconds. At 101 seconds, the frequency drops to 49.913 Hz across all buses due to the active power supply being insufficient to meet the load demand. After this drop, the frequency gradually rises back towards 50 Hz as the governors in the generators increase output power to restore equilibrium. The graph in Figure 4(b) shows the frequency at Pamona bus (275 kV), Bakaru bus (150 kV), the Tello bus (70 kV), and Panakukang bus (20 kV) after simulating the 37.8 MW load shedding of the Tolo wind power plant with an 8.437 MW battery energy storage system (BESS).

The 100-second simulation begins with the load shedding at 10 seconds, at which point the battery discharges 6.788 MW into the Sulbagsel system. The frequency remains stable at 50 Hz from 0 to 10 seconds, then rises to 49.924 Hz at 12 seconds due to the battery's rapid response. After this, the frequency increases towards 50 Hz from 14 to 100 seconds as governors adjust the output to achieve equilibrium, though temporary oscillations occur due to load and generation imbalance. Figure 4(c) shows that disconnecting the Tolo wind power plant causes the system frequency to drop to 49.913 Hz. However, with the installation of an 8.437 MW BESS, the frequency can rise to 49.924 Hz by discharging 6.785 MW, indicating a change in system frequency after BESS installation. Integrated generators in the interconnected system, as shown in Figure 4(d), experience generation oscillations. At 101 seconds, some generators increase output power in response to a signal indicating a drop in system frequency, helping stabilize it back to near 50 Hz. The graph shows that significant load shedding leads to frequency oscillations, indicating instability. This illustrates how interconnected generators in the Sulbagsel system adjust their output to maintain frequency stability around 50 Hz.

3.3. Simulation of power losses

The simulation results show the power flow in the Sulbagsel system, indicating that the BESS is installed at the bus with the highest load, which is the Tonasa bus. The BESS is simulated in two conditions: charge and discharge, and the results of active power losses in these two conditions will be compared. The power flow simulation before the installation of the BESS revealed active power losses in the Sulbagsel system of 36.70 MW, with the generated power from the system being 1443.85 MW + j658.04 MVAr. Meanwhile, the load connected to the system is 1407.15 MW + j303.52 MVAr. The power flow simulation results after the installation of the BESS at the Tonasa bus in both charge and discharge conditions can be seen in Table 2.

Table 2 shows the performance of the placement of the BESS at the Tonasa bus before and after its installation, in both charge and discharge conditions. The decrease in losses during the charge condition demonstrates that the BESS functions as a generator in the system, while the increase in losses during the discharge condition indicates that the BESS acts as a load in the system. To improve clarity, the simulation outcomes are also summarized in tabular form with performance metrics such as percentage frequency improvement, active power loss reduction, and relative efficiency gains. The summary is presented in Table 3.

Table 2. The simulation results before and after the installation of the BESS at the Tonasa bus

Power injection of BESS (MW)	Total losses		
	Before injection (MW)	After injection in the discharge condition (MW)	After injection in the charge condition (MW)
2	36.70	36.40	36.99
4	36.70	36.13	37.37
6	36.70	35.86	37.68
8	36.70	35.61	37.92

Table 3. Summary of BESS performance metrics in the Sulbagsel system

Scenario	Frequency deviation (Hz)	Frequency improvement (%)	Active power losses (MW)	Loss reduction (%)
Tonasa load shedding – without BESS	+ 0.143	-	36.70	-
Tonasa load shedding – with BESS	+0.112	21.7%	35.61	2.97
PLTB Tolo shedding – without BESS	-0.087	-	36.70	-
PLTB Tolo shedding – with BESS	-0.069	20.7%	35.86	2.29%

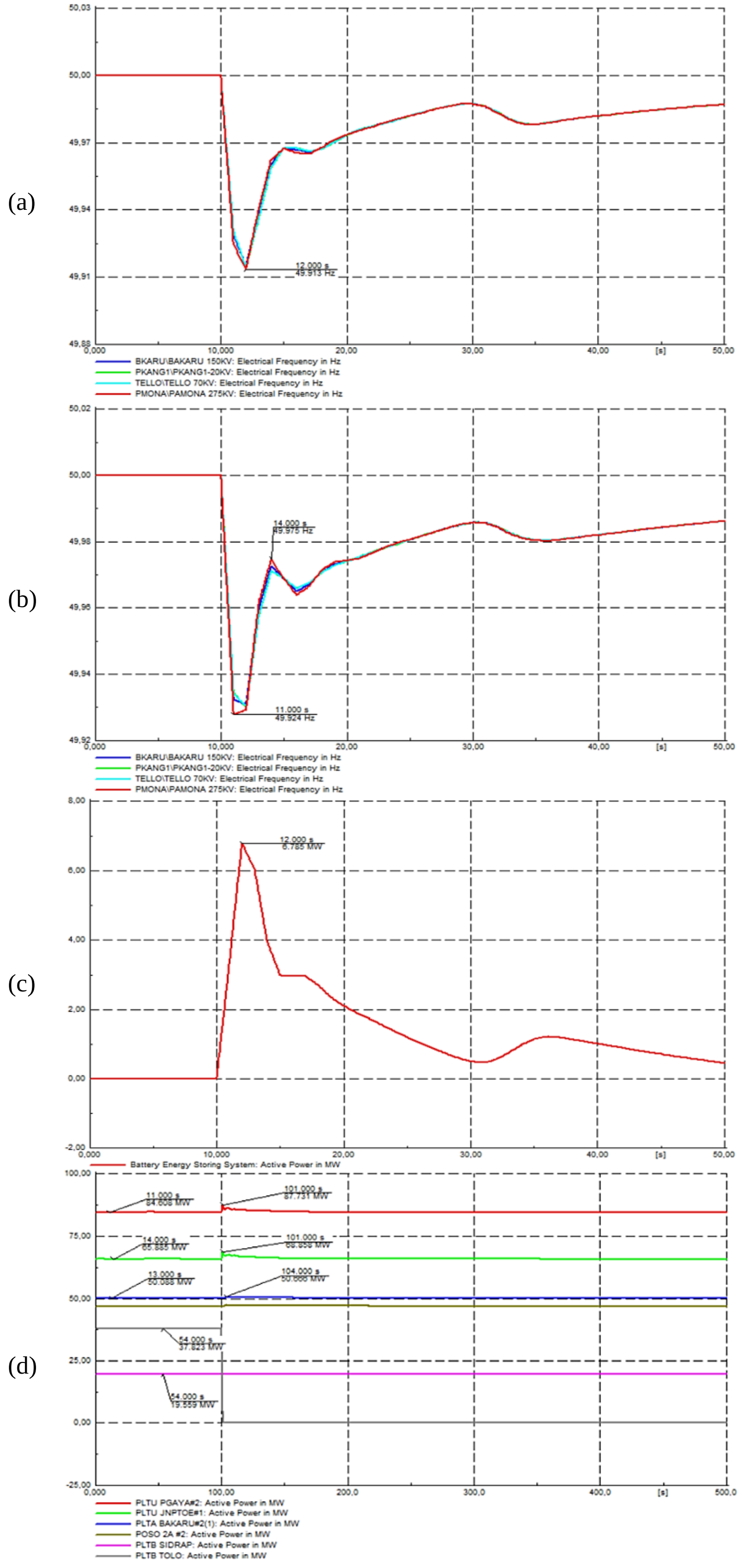

Figure 4. PLTB Tolo generation shedding simulation result: (a) frequency response without BESS, (b) frequency response with BESS, (c) power response without BESS, and (d) power response with BESS

This study positions its approach within existing literature by comparing it with common BESS placement methods such as genetic algorithm (GA), particle swarm optimization (PSO), mixed-integer linear programming (MILP), and AI-based techniques, which generally target multi-objective goals like reducing voltage deviations, minimizing power losses, and optimizing costs. In contrast, the proposed system strength index (SSI)-based method, combined with power loss analysis, offers a simpler yet practical solution, particularly suitable for systems with limited data and computational resources, making it highly relevant for the Sulbagsel grid. The comparison is summarized in Table 4.

As shown in the table, the SSI-based method introduced in this study focuses on frequency regulation and power loss minimization with relatively low computational complexity. Although it does not encompass multi-objective optimization like GA, PSO, or MILP, the approach provides a practical balance between technical accuracy and implementation feasibility, which can be extrapolated to similar interconnected or islanded power systems.

The results not only confirm that BESS improves frequency regulation and reduces active power losses but also highlight broader implications of placement on overall system behavior. When positioned at heavily loaded buses, BESS reduces transmission losses but may increase converter loading, influencing efficiency and thermal stress. Conversely, placement near renewable generators such as PLTB Sidrap enhances frequency support and smooths power fluctuations, thereby improving local power quality. These outcomes indicate that BESS placement decisions extend beyond loss reduction and frequency stabilization, directly affecting converter efficiency, voltage quality, and system-level stability. Thus, system planners must balance technical benefits with converter design considerations when determining optimal BESS locations.

Table 4. Comparative benchmarking of BESS placement methods

Method	Performance criteria (common)	Computational complexity	Applications in previous studies
Genetic algorithm (GA)	Voltage deviation, power loss minimization, and investment cost	High	[6]
Particle swarm optimization (PSO)	Power loss minimization, optimal sizing, efficiency	Medium - High	[8]
Mixed-integer linear Programming (MILP)	Multi-objective optimization of cost and reliability	High	[10]
AI/heuristic-based	Prediction and optimization using machine learning	High	[15]
SSI-based (this study)	Frequency regulation, power loss minimization	Low–Medium	-

4. CONCLUSION

This study has proposed various scenarios for integrating BESS into the interconnected Sulbagsel power system. Based on the SSI of all existing generators, the potential BESS capacity was determined to be 8.437 MW. The BESS placement simulation was conducted by examining frequency regulation alongside a generator or variable renewable energy (VRE), integrated with the Sidrap wind power plant (PLTB) in this study, and by minimizing active power losses on the bus with the highest load, specifically the Tonasa bus. Before the BESS installation, the system frequency reached 50.143 Hz during the Tonasa load shedding. After BESS installation, the system frequency was adjusted to 50.112 Hz. For the PLTB Tolo shedding scenario, the system frequency dropped to 49.913 Hz, but increased to 49.931 Hz after BESS installation. This outcome indicates that BESS can be utilized within the Sulbagsel system for initial frequency regulation before governor action. Placing an 8 MW BESS on the Tonasa Bus reduces active power losses in the Sulbagsel system by 1.09 MW in discharge mode, whereas the BESS increases active power losses by 1.22 MW in charge mode. This study does not account for BESS battery degradation and renewable energy generation uncertainty. The placement of BESS not only influences frequency regulation and power losses but also affects power quality, converter efficiency, and overall grid stability. Future studies should incorporate these factors into mathematical modeling to provide a more comprehensive overview of BESS operations and interactions with renewable energy sources. Such modeling could enable stakeholders to gain more accurate and practical insights for Indonesia's power system, making it a more effective tool for policy-making and investment decisions in energy storage and management. It should also address electromagnetic interference (EMI/EMC) issues and thermal performance of BESS converters, as these factors critically influence long-term reliability and operational efficiency. Future work will also include sensitivity analyses under varying load and generation conditions, as well as comprehensive fault-ride-through and contingency studies to validate the robustness of BESS placement.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Zaenab Muslimin	✓	✓	✓	✓		✓	✓		✓	✓		✓		✓
Indar Chaerah Gunadin	✓	✓	✓	✓		✓		✓	✓	✓		✓		✓
Fitriyanti Mayasari	✓	✓		✓	✓	✓			✓	✓	✓			✓
Muhira Dzar Faraby	✓	✓	✓	✓		✓	✓	✓	✓	✓				✓
Asma Amaliah					✓	✓		✓	✓	✓	✓		✓	
Isminarti					✓	✓		✓	✓	✓				

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this paper. This research was funded by the Lab-Based Education (LBE) Research Grant Program, Faculty of Engineering, Hasanuddin University, Fiscal Year 2024. The funding body had no involvement in the study design, data collection, analysis, interpretation, or the decision to publish the results. All authors independently contributed to the research work and preparation of this manuscript.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. The datasets include simulation files, frequency records, and power flow results generated using DIgSILENT PowerFactory for the Sulbagsel interconnected power system. Certain operational data obtained from PT PLN (Persero) are subject to confidentiality agreements and therefore cannot be publicly shared. However, derived results and processed data relevant to the analysis are available for academic and research purposes upon request.

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BIOGRAPHIES OF AUTHORS

Zaenab Muslimin was born on February 2nd, 1966, in Ujung Pandang, South Sulawesi, Indonesia. She graduated from Universitas Hasanuddin, Makassar, Indonesia, with a Bachelor's degree in 1990, a master's degree in 2004, and a doctorate in 2021. Her major field is Electrical Power Engineering. She is a lecturer at Universitas Hasanuddin, Department of Electrical Engineering. Her research interests include power system protection and measurement. She is also an active member of the Indonesian Engineers Union. She can be contacted at email: zaenab@unhas.ac.id.

Indar Chaerah Gunadin was born in November 1973 in Palopo, South Sulawesi, Indonesia, and was graduated from Universitas Hasanuddin, Makassar, Indonesia, with a bachelor in 1997 with a major in Electrical Power Engineering. He received master's and Ph.D. degrees from Sepuluh Nopember Institute of Technology (ITS), Indonesia, in 2006 and 2013, respectively. He is a professor at the Department of Electrical Engineering and currently, he is head of the relay, protection, and control laboratory in the Electrical Engineering Department of Universitas Hasanuddin, Indonesia. His research interests include power system stability, FACTS Devices, Artificial intelligence, and control. He is a member of the Indonesian Engineers Union, Indonesian Electrical Engineering Higher Education Forum, and Indonesian Electrical Engineering Experts Association. He can be contacted at email: indar@eng.unhas.ac.id.

Fitriyanti Mayasari was born on July 14th, 1983, in Makassar, South Sulawesi, Indonesia, and earned her bachelor's degree in Electrical Engineering from Universitas Hasanuddin, Makassar, Indonesia. She graduated from Universitas Indonesia in 2020 for her doctoral degree and in 2012 for her master's degree in Electrical Engineering. Currently, she has been a lecturer at the Department of Electrical Engineering, Universitas Hasanuddin, since 2006, and is actively doing her research in the field of sustainable energy. She can be contacted at email: fitriyantimaya@unhas.ac.id.

Muhira Dzar Faraby finished the S.T. and M.T. degree in 2012 and 2014 from the Department of Electrical Engineering, UNHAS, Indonesia, and the Dr degree in 2021 from the Department of Electrical Engineering, ITS Surabaya, Indonesia. Currently, he's a lecturer in the Department of Electrical Engineering, PNUP, Indonesia. His research interests are PQ, optimization of power systems, and stability of power systems. He can be contacted at email: muhiradzarfaraby@poliupg.ac.id.

Asma Amaliah received bachelor's degree (S.T.) in 2012 from the Department of Electrical Engineering, Hasanuddin University, Indonesia. Master's degree (M.T.) in 2016 from the Department of Electrical Engineering, Hasanuddin University. Currently, she is a lecturer in the Department of Electrical Engineering, Ujung Pandang State Polytechnic, Indonesia. Her research interests are in digital signal processing and embedded systems. She can be contacted at email: asmaamaliah@poliupg.ac.id.

Isminarti completed her Diploma in Electrical Engineering at Ujung Pandang State Polytechnic, her bachelor's degree in Electrical Engineering at Hasanuddin University, her master's in Electrical Engineering at Hasanuddin University, and her doctoral in Electrical Engineering at Hasanuddin University. She began focusing on writing after obtaining her doctorate. Currently, she is a permanent lecturer at the Aksa Mahmud Foundation, in the Mechatronics Engineering Study Program at Bosowa Polytechnic since 2013. She has expertise in automation engineering technology, including system modeling and identification, industrial automation electronics, and the internet of things (IoT). She can be contacted at email: isminarti@politeknikbosowa.ac.id.