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Enhanced intentional controlled islanding with BESS integration

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Article Info

ABSTRACT

Severe power system outages can lead to uncontrolled failures and system instability. Intentional controlled islanding is a strategy that deliberately splits the power system into balanced, stand-alone islands to ensure continuous electricity supply until full restoration. However, the execution of islanding may result in certain islands being unbalanced in terms of generation and load. In such cases, load shedding is implemented to achieve balanced stand-alone islands. Nevertheless, load shedding is not the best option as it will result in more users experiencing power disruptions. Therefore, this study explores the integration of battery energy storage systems (BESS) to enhance intentional controlled islanding, with the aim to form balance islands without the need to execute load shedding. This study evaluates the effectiveness of BESS in forming balanced islands and optimizing islanding strategies. The IEEE 30-bus and IEEE 118-bus test systems were used to validate the effectiveness of BESS in enhancing the intentional controlled islanding implementation. The results demonstrated the role of BESS in facilitating intentional controlled islanding, forming stable and balanced island operations without the need for a load shedding scheme. These findings highlight the potential of BESS to enhance the reliability and effectiveness of intentional controlled islanding.

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1. INTRODUCTION

Modern power systems face numerous challenges that impact their reliability and stability. These challenges include ageing infrastructure, load growth, energy crises, environmental concerns, unexpected events, and cyber threats. To address these issues, various solutions have been proposed, such as asset management, demand response, intentional controlled islanding, microgrids, and advanced monitoring systems [1]. Intentional controlled islanding, also known as network splitting, is a proactive strategy that isolates segments of the power grid into several islands during disturbances to prevent widespread blackouts [2], [3]. When a line disconnects due to a severe outage, other lines may overload and trip, leading to unintentional islanding, which can cause system instability and partial or total blackouts [4].

However, maintaining the power balance between local generation and load demand is the main challenge during intentional controlled islanding. Load shedding, which is a common method used to establish the load-generation balance during islanding, can sometimes lead to overloading or underloading within certain islands [5], [6]. Recent advancements in battery energy storage systems (BESS) offer an opportunity to address this issue by providing additional power support to balance the isolated islands after an islanding event [7]. BESS can minimise power imbalances within the formed islands, ensuring that the total active power generated and the total load in each island are balanced [8], [9].

This study explores the integration of BESS with intentional controlled islanding to attain load–generation balance in the power system [7]. BESS, known for their flexibility and rapid response capability, can enhance system resilience without resorting to disruptive load shedding practices. The optimal size of BESS is crucial to maximise their effectiveness within isolated grid segments. The most severe contingencies, such as generation loss and load loss, should be accounted for in the sizing process [10]. BESS operations are tailored to meet system requirements, providing up to 300 MW of power for peak reduction or renewable energy integration [11]. However, high-rate discharging can accelerate degradation, necessitating optimization to mitigate these effects [12]. The optimal placement of BESS in power networks is crucial to maximise their benefits and minimise power losses. Even though some studies are focused on minimising losses as the primary objective for BESS placement [13], other studies have shown that factors such as network structure, impedance analysis, and solar energy integration are important to determine the optimal size and placement of BESS [14]-[16]. Methods such as particle swarm optimization (PSO) can minimise power losses and voltage deviations in the distribution network [17], [18].

The objectives of this study are i) to analyze the deployment of BESS in the IEEE 30-bus and IEEE 118-bus systems, ii) to develop an algorithm that integrates BESS with intentional controlled islanding tailored to different system configurations, and iii) to evaluate the effectiveness of the BESS in forming balanced and resilient power islands [19]. Power flow analysis is used to model the network, solve non-linear equations, and ensure power balance using methods such as the Newton–Raphson method [20]. The inclusion of BESS has been shown to improve the dynamic behaviour of the power system, ensuring fast response, wide energy storage capacity, high efficiency, and a lifespan of 3–15 years [19], [21]. BESS can significantly reduce dependency on traditional load shedding practices in intentional controlled islanding scenarios. In addition, BESS can prevent uncontrollable frequency decline and minimise load shedding during unintentional islanding events by providing fast power recovery response [21]. This study advances the understanding of intentional controlled islanding methodology enhanced by BESS, with the aim to reduce dependency on traditional load shedding practices and improve overall power system reliability. However, the reliability of the BESS is influenced by different configurations and component selections, which should be considered when evaluating the overall system reliability [22].

2. METHODOLOGY

This study was carried out to investigate the integration of BESS with intentional controlled islanding, ensuring balanced power distribution across different system configurations. This study aims to enhance grid resilience and efficiency by determining the optimal size, placement, and integration of BESS using an advanced algorithm. The data from case studies presented in [23] were used in the analysis.

Figure 1 shows the flow chart of the overall methodology developed in this study, which begins by assessing the power flow and identifying potential bus placements for BESS installation. Next, the optimal size and placement of the BESS within the IEEE 30-bus or IEEE 118-bus test system are determined. These parameters are critical to ensure effectiveness of the BESS support during island formation, based on the findings of previous study [24], [25]. Once the optimal size and placement of the BESS are determined, the BESS are integrated into the intentional controlled islanding algorithm. This integration provides the necessary power support to unbalanced islands during intentional controlled islanding.
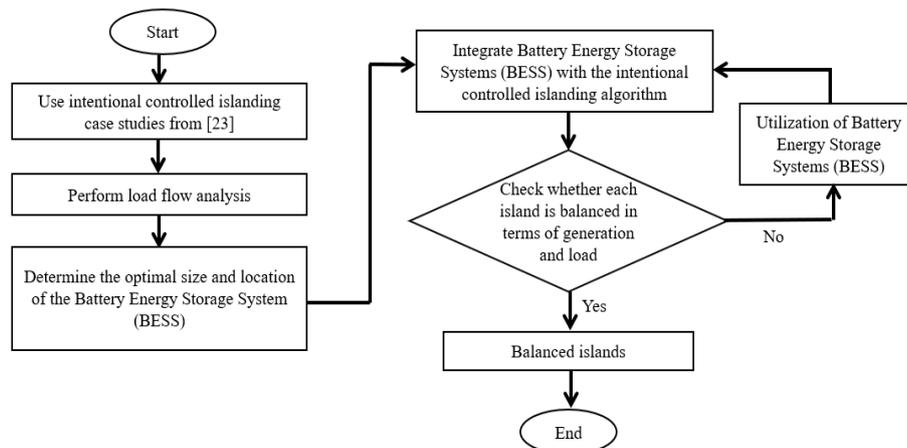

Figure 1. Flow chart of the overall methodology developed in this study

The final phase involves evaluating the performance of the BESS during intentional controlled islanding. Each island undergoes a balance check in failure scenarios to ensure load and generation equilibrium. In the event of load–generation imbalance, the BESS adjust to restore power balance in each island. If the load and generation are balanced in all islands, this indicates that the intentional controlled islanding strategy is successful, reflecting the capability of the algorithm to maintain a balanced power equilibrium without resorting to load shedding methods. The systematic approach employed to achieve the objectives in this study is outlined in subsequent sections.

2.1. BESS sizing

This analysis was conducted to verify the appropriateness of the proposed BESS size as a percentage of the total load. The load for each island was assessed based on the data from previous studies [24], [25]. The load data were gathered, where load shedding was used for intentional controlled islanding. The total loads before and after island formation were then determined based on the maximum load in each island. The percentage load after intentional controlled islanding was calculated to compare the maximum load in each island with the total load before intentional controlled islanding, ensuring that the percentage load did not exceed the recommended percentage, indicating that the BESS could support the island load if generation was insufficient. The BESS were sized at 80% of the total load, based on studies showing that the load for each island remained below this threshold during intentional controlled islanding, confirming that the BESS size was effective and reliable.

2.2. BESS placement

The placement of the BESS was selected based on the bus with the lowest total line losses, in order to minimise power losses, which are critical in power systems. The load data, including bus, transmission line, and generator values, were collected from previous studies [23]. Simulations were carried out by adding BESS values to the load bus, and the total line losses were determined for each bus load. The simulations facilitated in identifying the optimal BESS placement by highlighting the load buses with the lowest total line losses, ensuring the most effective placement of the BESS to minimise losses and enhance performance of the power system. Figures 2(a) and 2(b) show the IEEE 30-bus and IEEE 118-bus test systems with the BESS included, respectively.

2.3. Integration of BESS into the intentional controlled islanding algorithm

The integration process begins with deriving an intentional controlled islanding solution from the previous case study [23] using the modified discrete evolutionary programming (MDEP) algorithm. The MDEP algorithm is a metaheuristic optimization technique adapted for discrete decision variables. It is well-suited for performing intentional islanding, as it efficiently explores multiple cutset combinations while satisfying system constraints such as generation capacity limits and load–generation balance. Based on the case study in [23], load shedding was used to achieve load–generation balance in the islands following intentional controlled islanding. Islands were created within the power grid to prevent blackouts.

In this study, the novelty is the implementation of BESS instead of load shedding to balance the load and generation within the islands. After intentional controlled islanding, load flow analysis was performed to assess the load–generation balance within each island. It was crucial to identify the unbalanced islands. If all of the islands were balanced, the intentional controlled islanding strategy was successful. If there were unbalanced islands, the BESS were deployed to correct for power imbalances. The load-generation balance criterion is shown in (1).

$$\sum_i^n P_{i,gen} \geq \sum_i^n P_{i,load} \tag{1}$$

Where $P_{i,gen}$ is the generated active power for line i, $P_{i,load}$ is the supplied active power for line i, and n is the total number of buses in the island.

Figure 3 shows the flow chart of the steps involved in integrating the BESS with the intentional controlled islanding algorithm. The deployment of the BESS consisted of two steps: i) selecting the appropriate BESS within the affected islands and ii) determining the necessary power support based on the difference between load and generation. After BESS deployment, load flow analysis was performed again to ensure that the islands were balanced. If the load and generation were balanced for all islands, the optimal intentional islanding solution was achieved. If the load and generation were not balanced, further adjustments were made to the BESS to compensate for the power surplus or deficit. The optimal intentional islanding solution confirms that all islands operate with balanced load and generation, achieving a stable and efficient power distribution system. This methodology underscores the importance of BESS in maintaining grid stability during intentional islanding, optimizing island configurations, and preventing blackouts.
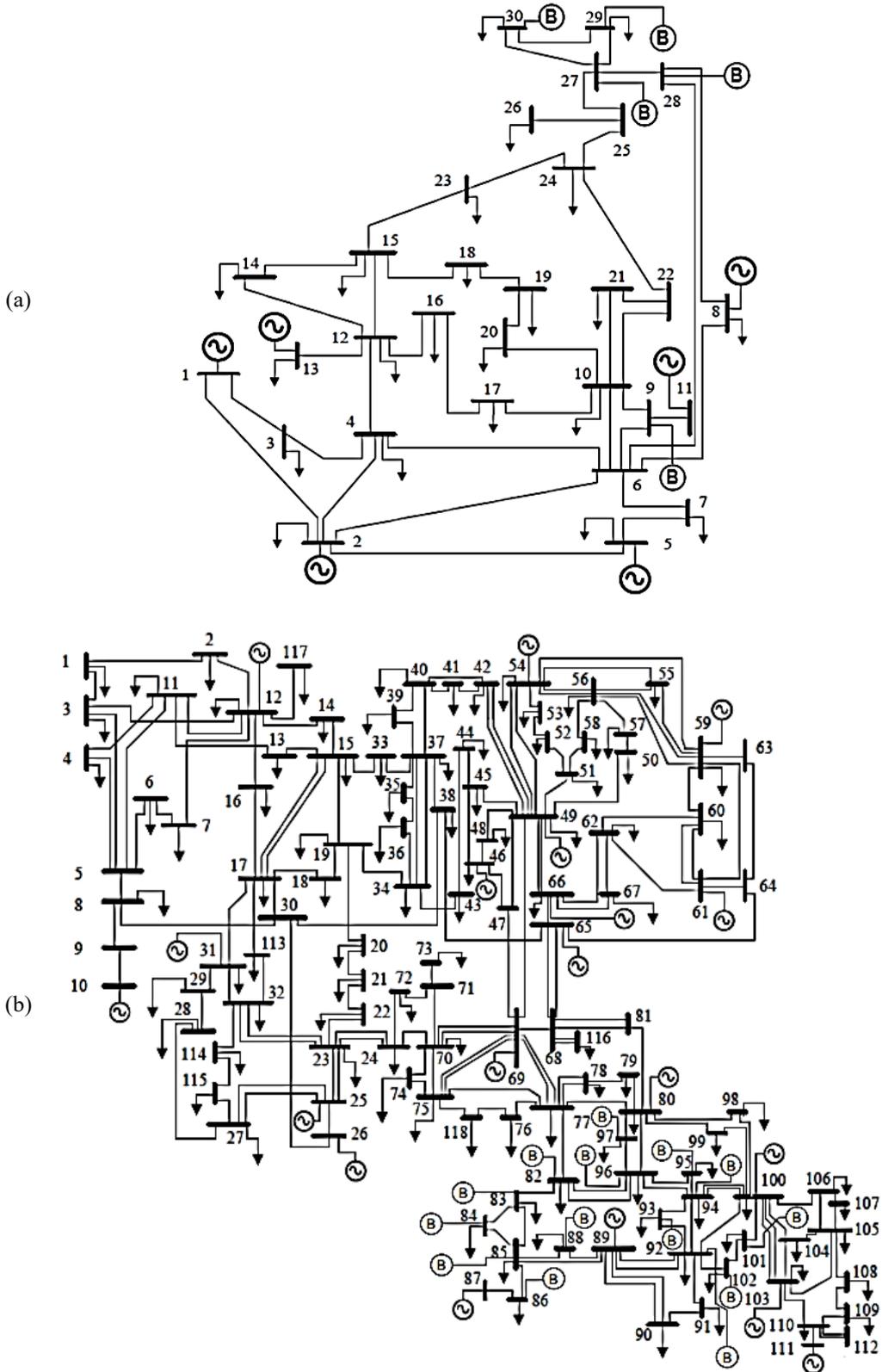
Figure 2. The placement of the BESS, as indicated by the B symbols for (a) IEEE 30-bus test system and (b) IEEE 118-bus test system
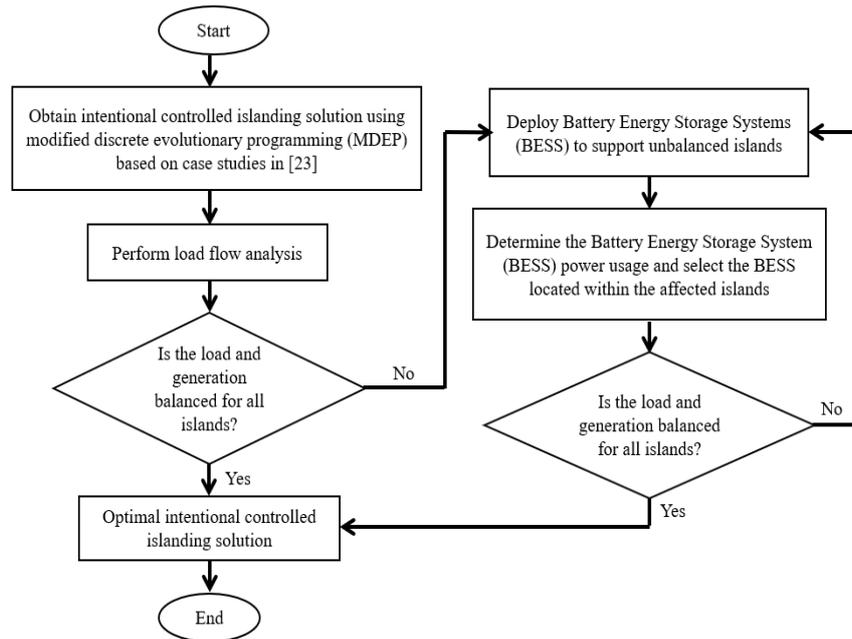
Figure 3. Flow chart of the steps involved in integrating the BESS with the intentional controlled islanding algorithm

3. RESULTS AND DISCUSSION

The IEEE 30-bus and IEEE 118-bus test systems were used to demonstrate and validate the effectiveness of the BESS in performing intentional controlled islanding by forming balanced islands. All the data, including the bus, transmission line, and generator values for these test systems, were obtained from [23]. To demonstrate the effectiveness of the BESS in performing intentional controlled islanding, the generator and load values were adjusted for each test system. The term pre-islanding refers to the operational condition of the power system before the execution of an intentional controlled islanding scheme, whereas post-islanding refers to the state of the power system after the intentional islanding has been executed. MATLAB R2015a software (The MathWorks, Inc., United States of America) on an Intel® Core™ i5-8250U central processing unit at 3.40 GHz with 8 GB of random-access memory was used to develop the codes.

3.1. Sizing and placement of the BESS in the IEEE 30-bus and IEEE 118-bustest systems

In this study, the recommended BESS size was 80% of the total load, with its placement determined by minimizing losses for each bus, as detailed in section 2. For the IEEE 30-bus test system, which comprises 6 generators, 24 load buses, and 41 transmission lines with a total load of 405.2 MW, the power required from the BESS was 325 MW. This was achieved by deploying five BESS (65 MW/260 MWh each) at buses 9, 27, 28, 29, and 30.

Similarly, for the IEEE 118-bus test system, which includes of 19 generators, 99 load buses, and 186 transmission lines with a total load of 5071 MW, the power required from the BESS was 4200 MW. This was attained by implementing 14 BESS (300 MW/1200 MWh each) at buses 82, 83, 84, 85, 86, 88, 92, 93, 94, 95, 96, 97, 101, and 102. The selection of the BESS size for the IEEE 30-bus and IEEE 118-bus test systems was based on the size of BESS installations in previous studies [26], [27], ensuring technical feasibility and relevance to real-world scenarios. The sizes and placements of the BESS in the IEEE 30-bus and IEEE 118-bus test systems are tabulated in Table 1. This approach ensures that the deployment of the battery energy storage system provides sufficient energy and power capacity to manage power imbalances during the implementation of intentional controlled islanding.

Table 1. Size and placement of the BESS in the IEEE 30-bus and IEEE 118-bus test systems

Test system	Size of each BESS	Placement of BESS (bus no.)
IEEE 30-bus	65 MW/260 MWh	9, 27, 28, 29, and 30
IEEE 118-bus	300 MW/1200 MWh	82, 83, 84, 85, 86, 88, 92, 93, 94, 95, 96, 97, 101, and 102

3.2. Case I: IEEE 30-bus test system

Two scenarios were considered to demonstrate the effectiveness of the BESS in performing intentional controlled islanding for the IEEE 30-bus test system, where the BESS were located at buses 9, 27, 28, 29, and 30 to maintain power balance. In scenario 1, the system was split into two islands based on generator groups: (1) G1 (buses 1, 2, 5, and 13) and (2) G2 (buses 8 and 11). The optimal islanding cutsets (i.e., transmission lines which would be disconnected to form islands) were found to be 2-6, 4-6, 5-7, 16-17, 18-19, and 23-24. The total active power generated (P_{gen}) and total load (P_{load}) for these islands before and after intentional controlled islanding, along with the maximum generator power limit and the total BESS capacity required to attain power balance are summarised in Table 2.

For island 1, with a maximum generator power limit of 700 MW, the total active power generated and the total load before intentional controlled islanding were 300.998 and 161.4 MW, respectively, resulting in a surplus of 139.598 MW. After intentional controlled islanding, the total active power generated was increased to 169.018 MW to match the total load of 161.4 MW, eliminating the need for BESS due to sufficient power generation within the island.

For island 2, with a maximum generator power limit of 200 MW, there was no active power generated within the island to meet the total load of 206.2 MW before intentional controlled islanding, creating a deficit of 206.2 MW. After intentional controlled islanding, a number of generators capable of supporting up to 200 MW were allocated from buses 8 and 11, leaving a deficit of 6.2 MW. To compensate for this deficit and account for potential line losses, the required BESS support was doubled, resulting in a total BESS capacity of 12.4 MW. Based on the results, island 1 can manage its load independently, whereas island 2 requires 12.4 MW from the BESS located at bus 9 to achieve power balance and meet its load demand effectively.

In scenario 2, the system was split into three islands: (1) G1 (buses 1, 2, 5, and 13), (2) G2 (bus 8), and (3) G3 (bus 11). The optimal islanding cutsets were determined to be 2-6, 4-6, 5-7, 6-9, 6-10, 16-17, 18-19, 23-24, and 24-25. The total active power generated and total load for the three islands before and after intentional controlled islanding, along with the maximum generator power limit and the total BESS capacity required to achieve power balance are presented in Table 3.

For island 1, with a maximum generator power limit of 700 MW, the total active power generated and total load pre-islanding were 300.998 and 161.4 MW, respectively, producing a surplus of 139.598 MW. Post-islanding, the total active power generated was decreased to 168.075 MW to match the total load of 161.4 MW. BESS were not required in this case.

For island 2, with a maximum generator power limit of 100 MW, there was no active power generated to meet the total load of 106.9 MW pre-islanding, creating a deficit of 106.9 MW. Post-islanding, a number of generators capable of supporting up to 100 MW were allocated from bus 8, leaving a deficit of 6.9 MW. To compensate for this deficit and account for line losses, the BESS located at bus 27 was deployed to provide 13.8 MW, ensuring that the island fulfilled the load demand.

For island 3, with a maximum generator power limit of 100 MW, there was no active power generated to meet the total load of 52.7 MW pre-islanding, resulting in a deficit of 52.7 MW. Post-islanding, the total active power generated from bus 11 was 53.189 MW, matching the load demand of 52.7 MW. Thus, BESS were not required in this case. Based on the results, islands 1 and 3 can manage their loads independently, whereas island 2 requires additional support from the BESS to achieve power balance and meet its load demand effectively.

Table 2. Intentional controlled islanding with BESS: analysis of scenario 1 based on the IEEE 30-bus test system

Island	Buses	Maximum generator power limit (MW)	Active power (MW)				Total BESS capacity required (MW)
			Pre-islanding		Post-islanding		
			Total P_{gen}	Total P_{load}	Total P_{gen}	Total P_{load}	
Island 1	1–5, 12–16, 18, 23	700	300.998	161.4	169.018	161.4	—
Island 2	6–11, 17, 19–22, 24–30	200	0	206.2	207.807	206.2	12.4

Table 3. Intentional controlled islanding with BESS: analysis of scenario 2 based on the IEEE 30-bus test system

Island	Buses	Maximum generator power limit (MW)	Active power (MW)				Total BESS capacity required (MW)
			Pre-islanding		Post-islanding		
			Total P_{gen}	Total P_{load}	Total P_{gen}	Total P_{load}	
Island 1	1–5, 12–16, 18, 23	700	300.998	161.4	168.0.75	161.4	—
Island 2	6–8, 25–30	100	0	106.9	112.056	106.9	13.8
Island 3	9–11, 17, 19–22, 24	100	0	52.7	53.189	52.7	—

3.3. Case II: IEEE 118-bus test system

Two scenarios were considered for the IEEE 118-bus test system to evaluate role of the BESS in intentional controlled islanding, where the BESS were located at buses 82, 83, 84, 85, 86, 88, 92, 93, 94, 95, 96, 97, 101, and 102 to achieve power balance. In scenario 1, the system was divided into two islands based on generator groups: (1) G1 (buses 10, 12, 25, 26, 31, 46, 49, 54, 59, 61, 65, 66, 69, and 80) and (2) G2 (buses 87, 89, 100, 103, and 111). The optimal islanding cutsets were determined to be 82-83, 94-96, 80-99, 95-96, and 98-100. The total active power generated and total load for the two islands before and after intentional controlled islanding, along with the maximum generator power limit and the total BESS capacity required to achieve power balance are summarised in Table 4.

For island 1, with a maximum generator power limit of 5027.2 MW, the total active power generated and total load before intentional controlled islanding were 3842.346 and 3396 MW, respectively, resulting in a surplus of 446.346 MW. After intentional controlled islanding, the total active power generated was decreased to 3501.758 MW to match the total load of 3396 MW. It was not necessary to deploy BESS in this case owing to the sufficient power generation within the island.

For island 2, with a maximum generator power limit of 1439.0 MW, the total active power generated and total load pre-islanding were 1424 and 1675 MW, respectively, creating a deficit of 251 MW. Post-islanding, the total active power generated was increased to 1762.402 MW to match the total load of 1675 MW. To compensate for the power deficit and account for potential line losses, BESS located at buses 84 and 85 were deployed to provide 472 MW, ensuring that the island fulfilled the load demand. Based on the results, it is evident that island 1 can manage its load independently, whereas island 2 requires additional support from the BESS to attain power balance and meet its load demand effectively.

In scenario 2, the system was split into three islands: (1) G1 (buses 10, 12, 25, 26, and 31), (2) G2 (buses 46, 49, 54, 59, 61, 65, 66, and 69), and (3) G3 (buses 80, 87, 89, 100, 103, and 111). The optimal islanding cutsets were 15-33, 19-34, 30-38, 24-70, 24-72, 78-79, 77-80, 68-81, and 77-82. The total active power generated and total load for these islands before and after intentional controlled islanding, along with the maximum generator power limit and the total BESS capacity required to attain power balance are tabulated in Table 5.

For island 1, with a generator power limit of 1576 MW, the total active power generated and total load before intentional controlled islanding were 1076 and 867 MW, respectively, resulting in a surplus of 209 MW. After intentional controlled islanding, the total active power generated was decreased to 897.466 MW to match the total load of 867 MW. Hence, BESS were not required in this case.

For island 2, with a generator power limit of 2874.2 MW, the total active power generated and total load pre-islanding were 2216.346 and 1819 MW, respectively, creating a surplus of 397.346 MW. Post-islanding, the total active power generated was decreased to 1866.108 MW to match the total load of 1819 MW. Likewise, it was not essential to deploy BESS in this case.

For island 3, with a generator power limit of 2016 MW, the total active power generated and total load pre-islanding were 1974 and 2385 MW, respectively, producing a deficit of 411 MW. Post-islanding, the total active power generated was increased to 2464.064 MW to match the total load of 2385 MW. To compensate for the power deficit and account for line losses, a BESS located at buses 82, 84, and 85 was deployed to provide 738 MW, ensuring that the island fulfilled the load demand. Based on the results, it is apparent that islands 1 and 2 can manage their loads independently, whereas island 3 requires additional support from the BESS to achieve power balance and meet its load demand effectively.

Table 4. Intentional islanding with BESS: analysis of scenario 1 based on the IEEE 118-bus test system

Island	Buses	Maximum generator power limit (MW)	Active power (MW)				Total BESS capacity required (MW)
			Pre-islanding		Post-islanding		
			Total P_{gen}	Total P_{load}	Total P_{gen}	Total P_{load}	
Island 1	1–82, 96–98, 113–118	5027.2	3842.346	3396	3501.758	3396	—
Island 2	83–95, 99–112	1439	1424	1675	1762.402	1675	472

Table 5. Intentional controlled islanding with BESS: analysis of scenario 2 based on the IEEE 118-bus test system

Island	Buses	Maximum generator power limit (MW)	Active power (MW)				Total BESS capacity required (MW)
			Pre-islanding		Post-islanding		
			Total P_{gen}	Total Pload	Total Pgen	Total Pload	
Island 1	1–32, 113–115, 117	1576	1076	867	897.466	867	—
Island 2	33–78 116, 118	2874.2	2216.346	1819	1866.108	1819	—
Island 3	79–112	2016	1974	2385	2464.064	2385	738

4. CONCLUSION

In this study, the integration of BESS with intentional controlled islanding was employed to achieve balanced stand-alone islands in power systems. The simulation results from both the IEEE 30-bus and IEEE 118-bus test systems demonstrated that BESS effectively mitigates power imbalances during post-islanding scenarios, enabling smooth transition to islanded operation without the need for load shedding. Specifically, by appropriately sizing and locating BESS based on system demands and loss minimization, it was possible to maintain supply-demand balance across all islands, thereby enhancing system resilience and reliability. Furthermore, the findings highlight that the use of BESS not only ensures the successful operation of each stand-alone island but also minimizes the number of affected consumers by eliminating unnecessary disconnections. This highlights the essential contribution of BESS to modern grid operations, particularly in facilitating intentional controlled islanding.

AUTHOR CONTRIBUTIONS STATEMENT

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

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C	:	Conceptualization	I	:	Investigation	Vi : Visualization
M	:	Methodology	R	:	Resources	Su : Supervision
So	:	Software	D	:	Data Curation	P : Project administration
Va	:	Validation	O	:	Writing - Original Draft	Fu : Funding acquisition
Fo	:	Formal analysis	E	:	Writing - Review & Editing	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [NZS], upon reasonable request.

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