POWER SYSTEM CONTROLLED ISLANDING EQUIPPED WITH BATTERY ENERGY STORAGE SYSTEMS (BESS)

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in partial fulfilment of the requirements for the degree of
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2024

DECLARATION

I declare that this thesis entitled "POWER SYSTEM CONTROLLED ISLANDING EQUIPPED WITH BATTERY ENERGY STORAGE SYSTEMS (BESS) is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

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APPROVAL

I hereby declare that I have checked this report entitled " POWER SYSTEM CONTROLLED ISLANDING EQUIPPED WITH BATTERY ENERGY STORAGE SYSTEMS (BESS) ", and in my opinion, this thesis fulfils the partial requirement to be awarded the degree of Bachelor of Electrical Engineering with Honours

Signature :

Supervisor Name : DR. NUR ZAWANI BINTI SAHARUDDIN

Date : 20/6/2024

DEDICATIONS

I would like to devote my thesis to my beloved parents and sibling who have given me constant support, love, motivation and pray for completing this project.

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ABSTRACT

Severe outages in power systems can result in cascading failures, leading to uncontrolled system splitting and instability. Intentional islanding is a remedial action that deliberately splits the system into balanced, stand-alone islands to ensure a continuous electricity supply until full restoration. To optimize controlled islanding, various optimization techniques are employed, with load shedding traditionally used to balance the islands post-splitting. This study explores the integration of Battery Energy Storage Systems (BESS) to enhance the effectiveness of controlled islanding, aiming to maintain power balance without relying on conventional load shedding. The IEEE 30-bus, 39-bus, and 118-bus systems are employed to develop innovative intentional controlled islanding strategies incorporating BESS, with a focus on power balance during islanding events. The methodology includes power flow analysis, BESS parameter analysis (size and location), and the development of a BESS integration algorithm into intentional islanding solutions. The main objective is to evaluate the effectiveness of BESS in forming balanced islands and optimizing intentional controlled islanding strategies. Findings reveal that an optimal BESS size is 80% of the total load, and strategic placement based on line loss analysis minimizes energy losses and enhances efficiency. The BESS optimization strategy is shown to be scalable and adaptable across different system sizes. Six case studies validate the effectiveness of BESS in managing power surpluses and deficits, supporting reliable island operations. These findings contribute valuable insights into BESS integration, providing a foundation for future work and practical applications in intentional controlled islanding strategies.
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ABSTRAK

Gangguan teruk dalam sistem kuasa boleh mengakibatkan kegagalan melata, yang membawa kepada pemisahan dan ketidakstabilan sistem yang tidak terkawal. Pepulauan yang disengajakan ialah tindakan pembetulan yang sengaja membahagikan sistem kepada pulau yang seimbang dan berdiri sendiri untuk memastikan bekalan elektrik berterusan sehingga pemulihan penuh. Untuk mengoptimumkan pulau terkawal, pelbagai teknik pengoptimuman digunakan, dengan penumpahan beban secara tradisinya digunakan untuk mengimbangi pulau selepas pemisahan. Kajian ini meneroka integrasi Sistem Penyimpanan Tenaga Bateri (BESS) untuk meningkatkan keberkesanan pulau terkawal, bertujuan untuk mengekalkan keseimbangan kuasa tanpa bergantung pada penumpahan beban konvensional. Sistem IEEE 30-bas, 39-bas, dan 118-bas digunakan untuk membangunkan strategi kepulauan terkawal yang disengajakan yang inovatif yang menggabungkan BESS, dengan tumpuan pada keseimbangan kuasa semasa acara pulau. Metodologi termasuk analisis aliran kuasa, analisis parameter BESS (saiz dan lokasi), dan pembangunan algoritma penyepaduan BESS ke dalam penyelesaian pulau yang disengajakan. Objektif utama adalah untuk menilai keberkesanan BESS dalam membentuk pulau yang seimbang dan mengoptimumkan strategi pulau terkawal yang disengajakan. Penemuan mendedahkan bahawa saiz BESS optimum ialah 80% daripada jumlah beban, dan peletakan strategik berdasarkan analisis kehilangan talian meminimumkan kehilangan tenaga dan meningkatkan kecekapan. Strategi pengoptimuman BESS ditunjukkan sebagai berskala dan boleh disesuaikan merentasi saiz sistem yang berbeza. Enam kajian kes mengesahkan keberkesanan BESS dalam mengurus lebihan dan defisit kuasa, menyokong operasi pulau yang boleh dipercayai. Penemuan ini menyumbangkan pandangan berharga ke dalam integrasi BESS, menyediakan asas untuk kerja masa depan dan aplikasi praktikal dalam strategi pulau terkawal yang disengajakan.

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CHAPTER 1

INTRODUCTION

1.1 Background

Electricity is used extensively in modern civilization for a variety of purposes, including industry, transportation, and housing. Power plants generate electrical energy, which is then transported to customers via a network of linked power lines to create electricity in the power system. The power system consists of distribution, transmission, and generation that will ensure the delivery of electricity to consumers. Safety, reliability, and system performance are priorities given the high reliance on electricity. However, disruptions in the power system can have serious implications for the safety, reliability, and overall performance of the system. Therefore, the increased demand for electricity will increase the possibility of outages, which can cause cascade failure. A cascading failure will cause the power system to malfunction and cause a blackout.

Experts have devised various methods to ensure the stability and reliability of power systems to reduce the effects of system failures. Among them are control action prevention [1], load shedding scheme [2], and automatic voltage regulation [3]. The intentional implementation of controlled islands is also one of the strategies to prevent the network from partial or total blackout. This approach helps to isolate affected areas, preventing failures from spreading throughout the system. After forming controlled islanding, addressing potential unbalances within each island is important. Initially, load shedding is often used to balance the islands by adjusting the power load to match the available generation on each island. Load shedding strategically curtails specific loads to ensure that the power generation and load are balanced. Load shedding ensures that power generation and load remain balanced.

Using a Battery Energy Storage System (BESS) is an alternate strategy to create a balanced island. By offering extra power support during controlled islanding, BESS may be quite helpful in creating balanced islands. As a dynamic energy source, BESS may provide extra power to make up for any imbalances in the supply and demand. A 50MW/75MWh BESS trial in Western Sydney is part of the Tropic Wings project in Australia, which is one of the successful BESS demonstrations. The Tropic Wings project focuses on the integration of battery electric vehicles (BEVs) and attempts to demonstrate the successful integration of two BESSs [4].

The primary objective of integrating a Battery Energy Storage System (BESS) into the intentional controlled islanding is to utilize BESS for balancing the islands by providing additional power generation. BESS, known for its energy storage capabilities can be leveraged to contribute additional power generation to ensure a balanced island on each island. The aim is to reduce the risk of large-scale blackouts and offer an efficient approach to maintaining the balance of power in intentional controlled islanding.

1.2 Motivation

Modern life is powered by electricity that runs everything from our homes to businesses and necessary services. Ensuring a consistent and reliable power supply when failure occurs is essential to technological progress, public safety, and economic growth. However, increasing energy demand poses more problems for power systems [5]. A secure power supply must be maintained in the face of these obstacles, which require creative solutions. One promising tactic to prevent cascading failures and improve system resilience is controlled islanding that isolates specific power system components. The integration of BESS into the Controlled Island scenario further increases the effectiveness and reliability of this strategy.

The motivation of this project is to address this challenge by integrating a Battery Energy Storage System (BESS) into intentional controlled islanding. Intentional controlled islanding is executed to prevent the network from partial or total blackout. However, intentional controlled islanding may have limited generation capacity, causing constraints in supplying the required load in each island after its implementation. Intentional controlled islanding requires a method that can help the generating capacity to supply the power to the load. The project aims to develop a Controlled Islanding implementation with BESS utilization. By leveraging advanced technology, the project endeavors to reduce downtime, economic losses, and disruptions to critical services.

1.3 Problem Statement

Intentional controlled islanding is a strategy used in power systems to prevent extensive outages and cascading failures. It involves splitting the system into smaller islands to limit the impact of disruptions [6]. To make intentional controlled islanding effective, it is crucial to maintain a balance between power generation and consumption within each island [7]. Traditional methods such as load shedding, while effective, inconvenience consumers and disrupt essential services, affecting various sectors and compromising power system reliability [8].

This research aims to find an innovative approach to intentional controlled islanding in power systems. It explores the integration of Battery Energy Storage Systems (BESS) to maintain power balance without relying on load shedding.

1.4 Objective

The integration of Battery Energy Storage Systems (BESS) into the Intentional Controlled Islanding approach for power systems is the primary objective of this study. To meet this goal, the following targets have been established:

1. To analyze the size and location of BESS for the IEEE power system network for intentional controlled islanding implementation.

2. To integrate the BESS into an intentional controlled islanding algorithm.

3. To evaluate the effectiveness of the utilization of BESS in performing intentional controlled islanding by forming balanced islands using IEEE 30-bus, 39-bus, and 118-bus system.

1.5 Scope of Study

This project focuses on the integration of Battery Energy Storage Systems (BESS) in the intentional controlled islanding strategy for power systems, focusing on scenarios where traditional load shedding methods are not used. The scope of this study are presented as follows:

i. Case studies analyzed in this research are based on previous studies [9].

ii. This study focuses on the IEEE 30-bus, IEEE 39-bus, and IEEE 118-bus systems, defining the desired group of generators and islands based on existing work [9].

iii. The determination of the size and location of BESS considers only the discharge value.

Acknowledging inherent limitations and assumptions, this study aims to provide practical insights into reducing dependence on load shedding. The final report will offer a professionally articulated overview, emphasizing the potential benefits of intentional controlled islanding with BESS and laying groundwork for future improvements and research.

CHAPTER 2

LITERATURE REVIEW

2.1 Power Networks

Power system network consists of generation stations, transmission lines, and distribution infrastructure, all designed to ensure the reliable delivery of electricity to end-users [10]. The network is intended to operate in a coordinated manner, with a coordinated flow of power from generation sources through transmission lines to consumers.

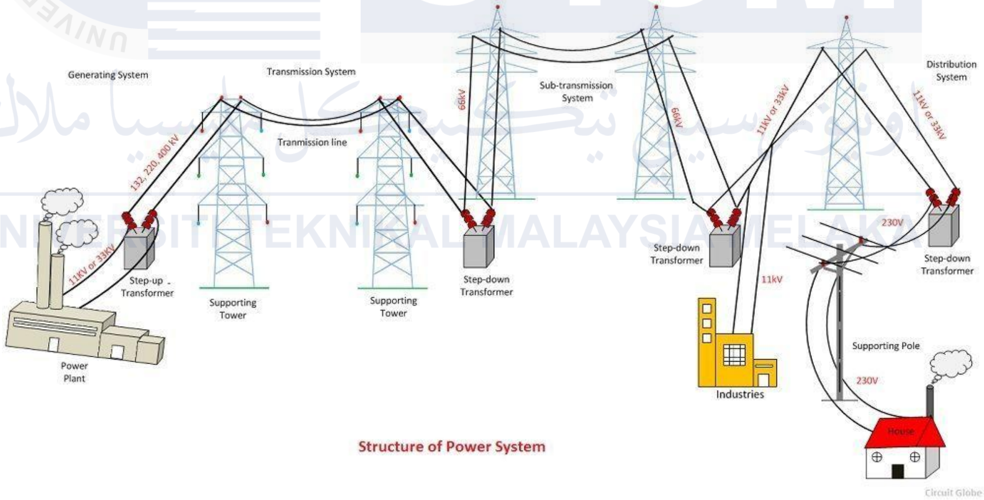

Figure 2.1: Structure of Power System [10]

Power systems play an important role in supporting industrial, business, and residential functions, with reliability being of utmost importance [11]. According to Energy Production and Consumption [12], the average global energy consumption is around 1% to 2% per year, increasing demand for electricity has prompted continuous efforts in the power system industry to improve distribution, transmission, and generation techniques. However, the power system faces challenges in maintaining a stable and reliable electricity supply because of rapid population growth, urbanization, and industrialization. The growing demand indicates an increased need for efficient power system management and control. Hence, the power system industry persists in advancing innovative technologies and solutions to always ensure a consistent and stable power supply.

2.2 Power System Failure

Power system failure refers to the loss of electrical power in a power system network. Disturbances in an electrical power system can destabilize what was once a stable system. Factors contributing to power system failure include atmospheric phenomena, technical issues, and human factors [13]. Table 2.1 presents the primary causes of power system failure and their impacts on the overall system.

Table 2.1: The main causes of power system failures [13]

Cause of failure	**Effects on the power system**
Atmospheric phenomena	-Extremely high temperatures: Challenges to the cooling systems' ability to function in traditional power plants -Abnormally low temperature: Potential for hard rime buildup on electrical lines -Strong wind: Overhead wires collapse -Storms: A phenomenon when an atmospheric discharge damages components of the electricity system.
Technical causes	-Device malfunctions and technical issues that are also brought on by ageing devices -Insufficient power reserves or production capacity - A power imbalance in the system accompanied by a concurrent rise in the demand for energy -Automation, control, and communication system unreliability - Absence of protective triggers following hazard identification
Human factor	-System operators' mistakes or omissions as well as careless exploitation - Making poor choices when it comes to managing the power system, particularly when the likelihood of a failure is rising. -Vandalism - Willful damage to network equipment, such as insulators in overhead cables -The Terror - Cyberattack risk for networks used for distribution and transmission

These failures can range from minor disruptions to widespread blackouts, resulting in significant financial loss, public inconvenience, and serious risks to public safety. Examples of notable blackouts include the North American blackout in 2003, the

European blackout in 2006, the Indian blackout in 2013 [14], and the Malaysian blackout in 1996 [15].

2.3 Mitigation Techniques for Preventing Blackouts

There are numerous strategies and technologies employed to maintain continuous electricity supply during power outages. Power system operators and planners typically utilize a combination of preventive, corrective, and remedial measures to minimize the likelihood and mitigate the impacts of outages. Effective outage mitigation techniques aim to reduce or eliminate cascading failures that lead to large-scale power outages. Various techniques have been proposed and implemented to enhance power system resilience, as detailed below.

2.3.1 Preventive Control Action: Generator Rescheduling

The main goal of preventive control techniques is to identify the measures that need to be taken in order to keep the power system from losing synchronism when potentially dangerous events are predicted. Preventive security control aims to ensure that the system is capable of handling unforeseen situations in the future by proactively preparing it during regular operation. This may entail taking steps like load restriction, reactive compensation, network switching, and generation rescheduling [16]. Generator rescheduling is the process of adjusting the operating schedules of generators to meet load demand and maintain system stability [17]. It involves redistributing generation from one area to another while ensuring that line overloads are not exceeded. This redistribution is calculated using proportionality. If generator rescheduling cannot ensure safe operation, the next step is to consider optimal load shedding or disconnecting the affected area, creating an islanded system [16].

2.3.2 Load Shedding Schemes

In order to maintain system stability during emergency conditions by balancing the supply and demand of electrical energy, load shedding schemes are intentionally implemented [18]. There are two methods: static and dynamic load shedding, as mentioned by [19]. Static load shedding involves predetermined, fixed amounts of load shedding based on set priorities, while dynamic load shedding adjusts in real-time based on the actual state of the system. Imbalances between power generation and consumption can cause issues such as voltage and frequency drops, leading to frequency instability. To address this, power companies employ techniques like Under Frequency Load Shedding (UFLS) and Under Voltage Load Shedding (UVLS) to isolate dangerous areas from electricity sources [20]. However, these methods can sometimes cause inadvertent trips at a distance, overloading transmission lines and lowering voltage levels elsewhere in the grid.

2.3.3 Automatic Voltage Regulators (AVR) and Power System Stabilizers (PSS)

Automatic Voltage Regulator (AVR) manages voltage fluctuations and maintains system stability [21]. The purpose of this device is to control the voltage supply across the electrical power system. An unstable voltage is converted to a stable voltage by a voltage regulator. Changes in power demand can cause instability in voltage such voltage is a threat to the equipment present in the power system. Power system transformers, generators, feeders are some of the places where voltage control devices are located to control such fluctuations. Voltage changes can be controlled through many voltage regulators in a power system. Additionally, a power system stabilizer is a type of control device used to dampen power system oscillations and improve dynamic stability and response to disturbances. Power system stabilizers (PSS) play an important role in improving oscillation damping in power systems through excitation regulation [22]. They usually obtain information such as shaft speed, terminal frequency and power so that they stabilize the system effectively. This controller helps to ensure that there is still stability in it, thereby preventing any kind of disruptive oscillations that can cause disruptions in the reliability and efficiency of the service.

2.3.4 Intentional Islanding

Intentional controlled islanding in power systems refers to the deliberate separation of a transmission line from the rest of the network, creating an "island" that functions independently. This approach serves as a preventive measure to avoid failures and major blackouts. The power balance of each island is a crucial factor that needs to be emphasized when forming intentional islands. The primary goal of islanding is to protect the power system from total collapse during significant disruptions [23] which can be triggered by events such as natural disasters, equipment malfunctions or other unforeseen circumstances. By isolating an area of the system critical loads can still receive power supply minimizing the impact, on consumers and preserving services.

For instance, the intentional islanding method suggested in [9] utilizes the Modified Discrete Evolutionary Programming (MDEP) algorithm to derive an optimal intentional islanding strategy for the IEEE 30-bus system. This strategy results in the creation of two separate islands, labeled Island 1 and Island 2, each consisting of 12 and 18 buses, respectively. Notably, the red dashed lines represent cutsets in the system. After the intentional islanding, it is imperative that these two isolated islands are balanced concerning the total power generated and total load. Figure 2.2 shown one line diagram of proposed method.

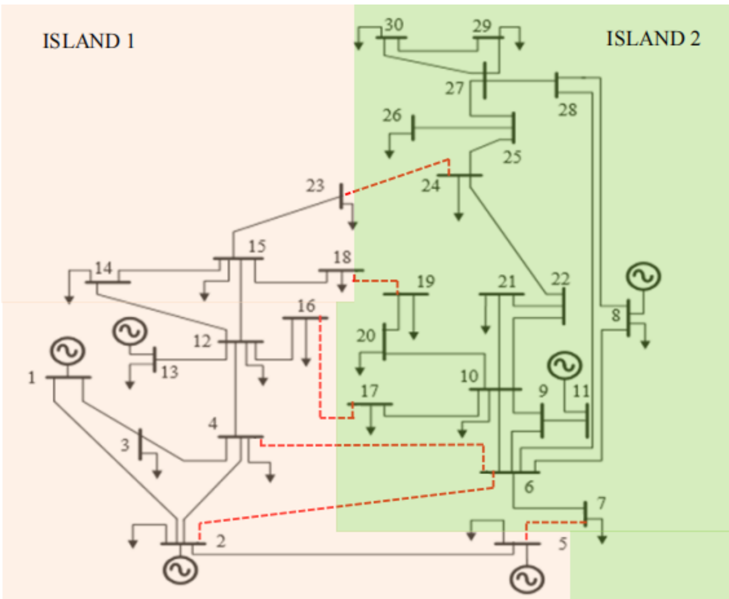

Figure 2.2: One line diagram for IEEE 30-bus system using MDEP

2.4 Strategies for Maintaining Power Balance during Islanding

Intentional controlled islanding plays a crucial role in maintaining power system stability during failures. However, it faces various challenges in balancing power within isolated islands, including:

i Load Shedding: When the power system is divided into islands, imbalances between power generation and demand can occur, leading to a reduction in power supply to prevent blackouts [24].

ii Power Imbalance: One island may generate sufficient power while another struggles to meet demand, causing generators in one island to be overloaded and underloaded in another [25].

In order to overcome these challenges, implementing intentional controlled islanding strategies requires adherence to several constraints [9] Separation and Synchronization Constraints (SSC) ensure that the system is divided into sections while maintaining synchronization for stability. Power Balance Constraints (PBC) are crucial for maintaining balance within each section, avoiding overloading or underutilization of generation, and ensuring a continuous power supply to loads. Rated Value and Limit Constraints (RLC) set limits on parameters such as voltage and power flow within sections, protecting equipment, preventing damage, and optimizing performance.

To achieve balanced power distribution during islanding, various methods are employed, including load shedding and the integration of Battery Energy Storage Systems (BESS). These methods aim to optimize the separation strategy by achieving a balanced power distribution. BESS can significantly contribute by distributing electricity to meet excess loads during isolation.

2.5 Battery Energy Storage Systems (BESS) in Intentional Islanding

Battery energy storage systems (BESS) can be used in intentional controlled islanding to provide backup power during grid outages. In the intentional controlled islanding scenario, the power system is separated into several islands following critical conditions to protect the system. BESS can be used to minimize the power imbalance in the formed islands [26].

Battery energy storage systems (BESS) are becoming increasingly attractive because BESS connections have an impact on grid stability and reliability. According to [27], BESS provides various support functions to the power grid, including frequency regulation, voltage support, stabilization and emergency response services that will balance the grid and maintain stability. Additionally, BESS can respond quickly to fluctuations in supply and demand, preventing voltage sags and outages, thus improving grid stability.

2.5.1 BESS Technologies

According to [28] and [29], various battery technologies are used in grid-sized Battery Energy Storage Systems (BESSs, typically above 1 MW in power capacity). The type and characteristics of each battery are shown in Table 2.2.

Table 2.2: Technologies of BESS

Type of Battery	**Key Characteristics**
Lead Acid Batteries	Lower energy density but good charge/discharge efficiency.
Lithium-ion Batteries	High energy density, efficient charging/discharging, low self-discharge.
Nickel-Metal Hydride Batteries	Outstanding energy density, charge/discharge, and cycle length; low self-discharge.
Sodium-Sulfur Batteries	Outstanding cycle endurance, minimal self-discharge, exceptional specific power, and high charge/discharge efficiency.
Flow Batteries	excels in charge/discharge efficiency, cycle length, low self-discharge, specific power, and energy density.
Supercapacitors	Offers high power output, short-duration discharge; gaining popularity as an alternative.

Based on Table 2.2, each type of battery exhibits distinct characteristics. Among these, lithium-ion batteries have become dominant due to cost reductions and excellent performance. However, future expansion may be constrained by the availability of rare earth materials. As they continue to be developed, two new options that make use of more readily available materials are emerging: sodium-ion and flow batteries.

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2.5.2 BESS Challenges

There are many challenges that need to be addressed when integrating BESS into a power system. According to [30], Choosing the right BESS placement, size, and operation to enhance network performance is one of the issues. To guarantee that BESS is integrated into the power system as effectively as possible, optimising the placement, size, and functioning of BESS is a crucial task that has to be carefully considered and strategically planned for. To maximise the utilisation of the BESS, a number of aspects need to be examined and taken into account, including its location and size.

2.5.2.1 Size of BESS

The optimal size of a Battery Energy Storage System (BESS) to integrate into a power system depends on various factors. The ideal size of BESS has been the subject of several research in the literature for a variety of reasons. In [31], the optimal BESS size is determined by considering operational and security factors to protect the microgrid from potential energy source attacks. In [32], factors including network structure, impedance analysis, and solar energy integration are used to find the minimum BESS size and the best location to improve the voltage profile across nodes. In [33], the size of BESS in a microgrid system involves factors such as power-to-space ratio, energy efficiency, lifetime, distance, cost, maintenance, technology and safety. In [34], the optimal BESS size in a microgrid study is determined by balancing operating costs and capital investment. The study looked at three types of batteries and considered network parameters and losses to find the best size.

The largest BESS capacity, at 300 MW/1200 MWh with a 4-hour discharge capability [35]. allows for flexible adjustment of discharge values according to specific needs and applications [36]. According to [37], the duration that a BESS can support depends on its energy storage capacity relative to its discharge rate, with higher storage capacities (in kWh) supporting longer durations at a given discharge rate. The discharge rate and support duration are inversely proportional; lower discharge rates result in extended support periods. BESS operations are tailored to meet system requirements, allowing for full 300 MW power supply as needed for peak reduction or renewable energy integration [38]. However, high-rate discharging can accelerate degradation, necessitating optimization to mitigate these effect [39]. According to [40], BESS duration is calculated by dividing its capacity in MWh by its rated power in MW, crucial for determining charge and discharge cycle times.

In summary, BESS can supply full capacity as required by optimizing its settings based on system needs, managing heat, ensuring efficient charging, and controlling discharge to maximize operational life. Careful management of discharge processes is essential to avoid excessive degradation. Each bus can be equipped with the highest suitable BESS capacity, with discharge settings tailored to achieve desired load demand.

2.5.2.2 Location of BESS

The optimal location of a Battery Energy Storage System (BESS) to be integrated into the power system depends on various factors. The ideal location of BESS has been the subject of several research in the literature for a variety of factors.

According to [41], In order to overcome the shortcomings of solar photovoltaic distributed generation (SPVDG), which intends to lower power loss and enhance the voltage profile, the integration of BESS with SPVDG is the main emphasis. In contrast [42], uses Teacher Learning Based Optimisation (TLBO) to optimise the usage of BESS in a radial distribution system. TLBO takes into account power loss, investment, cost, and operational expenditures of BESS in order to increase system dependability. According to [43], aims to reduce power loss and reduction of voltage deviation in the distribution network. While for [33], aims to minimize power loss in the microgrid and ensure that BESS supplies sufficient energy to all loads by using Particle Swarm Optimization (PSO) to determine the optimal location that minimizes power loss in the microgrid system.

In conclusion, power loss is very important to emphasize in determining the location of BESS. This is because, it can reduce the negative effects and ensure that the power supply sent by the BESS to the load does not decrease. BESS placed in a place where less power loss will be preferred.

2.6 Power Flow Analysis

Power flow analysis is fundamental in power system engineering. It is important to understand to ensure the stable performance of the electrical network. According to [44], the important points in the analysis of power flow and the methodology used in the analysis of power flow have been shown, including:

1. Network Representation: The power system is modeled as an interconnected network consisting of buses and branches. Buses denote different points in the system, while branches represent the interconnections between these points. Various types of buses, such as generator buses, load buses, and slack buses.

2. System Equations: Power flow analysis relies on a set of nonlinear algebraic equations derived from Kirchhoff's law and power balance equations. Key variables include the magnitude and angle of the complex voltage on each bus.

3. Bus Classification: Different buses play specific roles in the power system. The generator bus marks the point where electrical power is injected, the load

bus represents the point where power is consumed, and the slack bus serves as a reference point.

4. Power Balance Equation: The power balance equation ensures that the total power injected at the generator bus is equal to the total power consumed at the load bus, considering losses and reactive power. This equation also considers line loss which shows the actual power lost during transmission.

5. Admittance Matrix (Y-Bus): Power systems are often represented using an admittance matrix (Y-bus) derived from impedance parameters. The Y-bus, combined with the bus voltage and form the basis of the power flow equation. After that, it will contribute both reactive and real power components.

6. Power Flow Equation: Using bus voltage and system characteristics, the power flow equation represents the actual and reactive power at each bus. This equation includes a term for line loss. Acknowledging the inevitable power dissipation along transmission lines.

7. Numerical Solution Method: Since the power flow equation is not linear, an iterative numerical method is used for its solution. Methods like the Newton-Raphson and Gauss-Seidel are frequently employed. Every time you solve the resulting system of linear equations, the Newton-Raphson approach linearizes the power flow equations and makes the process easier.

8. Convergence criteria: A power flow solution is considered converged when the changes in voltage magnitude and angle between successive iterations are within predefined acceptable limits. The convergence criterion also ensures that line losses are accurately represented in the solution.

In power systems, power flow equations are nonlinear and must be solved iteratively due to power being known rather than current. This analysis, integral to power system design and operation, can elucidate the power system's balance when implement intentional controlled islanding.

2.7 Chapter Summary

The discussion on power network structure and operation underscores the critical role of maintaining a reliable electricity supply. However, there is a constant threat of disruptions with potentially devastating consequences such as widespread blackouts. The main causes of power system failure and their effects have been discussed in this chapter. Subsequently, various techniques for mitigating power system failures are explored and have been discussed in this chapter.

Intentional islanding emerges as a promising approach for preventing widespread blackouts by isolating affected areas. Nevertheless, it poses challenges in maintaining a power balance within each isolated island. Load shedding, while effective, can disrupt critical services and inconvenience consumers. This identified gap motivates the research project to explore alternative solutions.

The review of BESS and its applications reveals its potential to address the power balance challenge during islanding. BESS can act as a dynamic energy source, compensating for imbalances between generation and demand. Through the analysis of the optimal size and location of BESS for islanding scenarios, valuable insights into its strategic integration are gained. The importance of power flow analysis in understanding and ensuring the balance performance of the power system within isolated islands is also discussed.

This chapter establishes a foundation for the project, linking existing literature with the objectives of exploring BESS integration in controlled islanding and developing an algorithm for its implementation. In the subsequent chapters, deeper exploration of specific methodologies and presentation of research findings on BESS optimization and effectiveness in maintaining balanced islands will be explained.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This research aims to explore intentional controlled islanding strategies in power systems by integrating Battery Energy Storage Systems (BESS). Building on a comprehensive literature review and problem identification, this study utilizes data from the IEEE 30-bus, 39-bus, and 118-bus system to develop innovative strategies for intentional controlled islanding. The primary objective is to achieve balanced power systems through strategic placement and effective utilization of BESS. The following methodology outlines the systematic approach employed to address challenges related to power imbalances during islanding events.

3.2 Overall Research Methodology

This research investigates intentional controlled islanding strategies integrated with Battery Energy Storage Systems (BESS) through a detailed literature review and problem identification. Utilizing data from the IEEE 30-bus, 39-bus, and 118-bus systems, the study develops an innovative analysis to integrate BESS into intentional controlled islanding. The primary objective is to optimize the placement of BESS to achieve balanced power systems, as demonstrated through comprehensive validation studies. The overall research methodology is illustrated in Figure 3.1, detailing each stage discussed in subsequent subtopics.

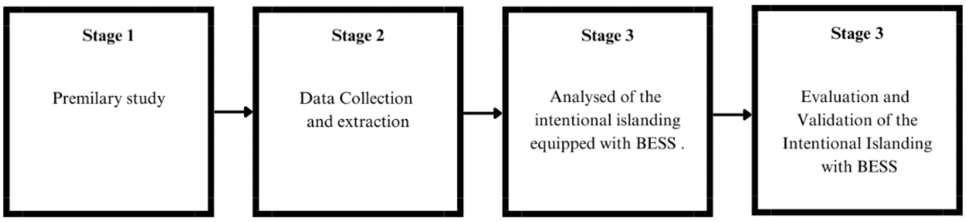

Figure 3.1: Flow Chart of Overall Research Methodology

3.2.1 Stage 1: Preliminary Study

In the initial stage, an exploration of journals, books, theses, and authoritative sources was conducted to collect information related to the research topic. This involved conducting an in-depth literature review focusing on intentional strategies and methodologies involving the use of BESS. Research problems have been identified, and specific objectives have been set to address the challenges highlighted in Chapter 1.

3.2.2 Stage 2: Data Collection and Extraction

Data for analysis was obtained from the IEEE 30-bus, 39-bus, and 118-bus test system. This stage involves extracting relevant data from [45] and [46] to support the subsequent analysis.

3.2.3 Stage 3: Analysis of Intentional Islanding equipped with BESS

This critical stage involves determining the size and location of the BESS before integration into the test system. In contrast to the traditional load shedding method, this study introduces an approach integrating BESS into the optimization process. Utilizing data from previous studies, a load flow analysis was conducted on the IEEE 30-bus, 39-bus, and 118-bus test system, the details of which are described in this chapter.

3.2.4 Stage 4: Evaluation and Validation of the Intentional Islanding Algorithm with BESS

At this stage, Intentional controlled islanding, which is now integrated with BESS, has been thoroughly evaluated and validated through a series of case studies. The evaluation process consists of the BESS's ability to balance load and generation.

3.3 Proposed Methodology

The flow chart shown in Figure 3.2 presents a structured approach to integrating Battery Energy Storage Systems (BESS) into intentional controlled islanding in power system networks.

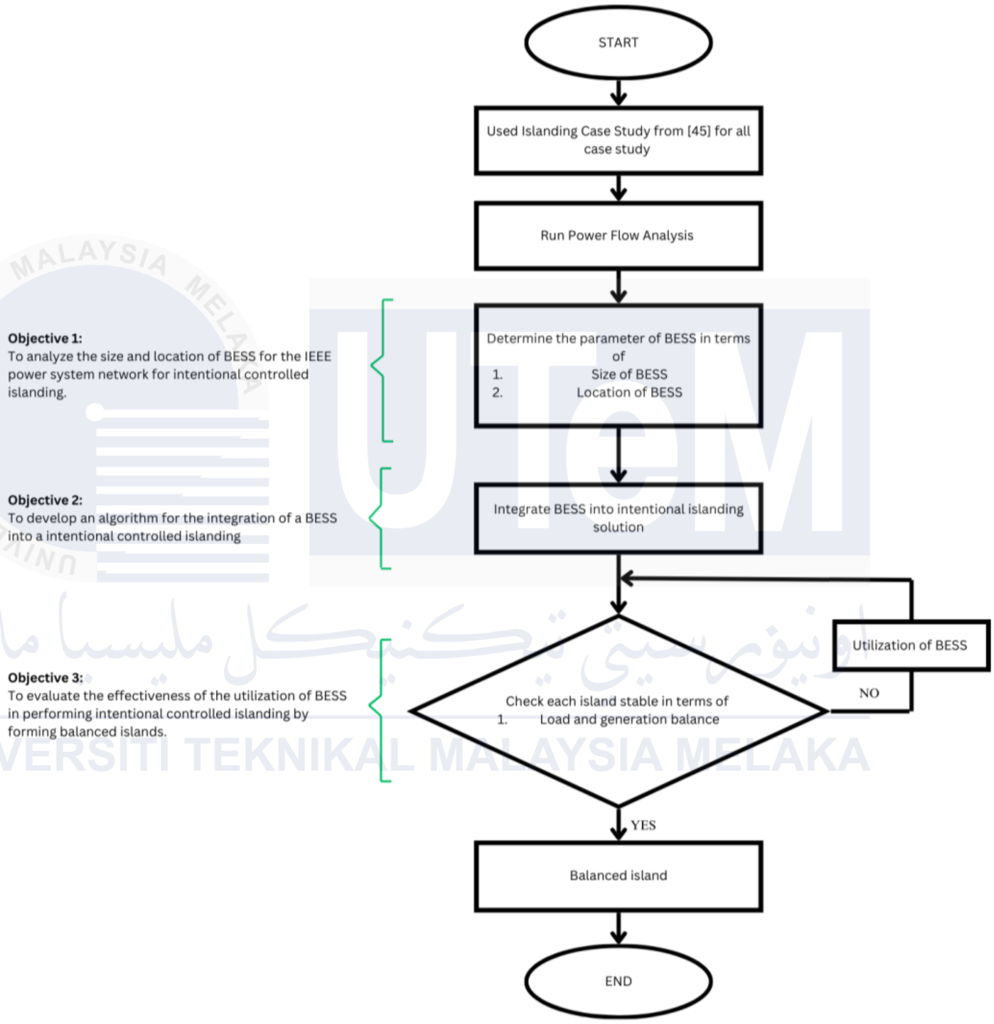

Figure 3.2: Flow Chart of Proposed Methodology

The data used for this analysis is sourced from the case study in [45]. The process commences with a power flow analysis of the IEEE test system using the Newton-Raphson method to determine the total load across the network. This initial step evaluates power flow, facilitating BESS parameter analysis and identifying bus for potential enhancement.

Subsequently, the focus shifts to BESS parameters, encompassing the optimal determination of size and installation location within the IEEE test system.

These parameters are crucial to ensure effective BESS support during island formation, informed by prior studies. This process aligns with Objective 1, aimed at analyzing BESS size and location for intentional controlled islanding in the IEEE power system network.

Once the BESS parameters are determined, the BESS is then integrated into the intentional controlled islanding algorithm. This integration of BESS will provide the necessary power support to the part of the island that is not balanced in terms of power generation and load demand during intentional controlled islanding. This process will achieve objective 2, which is to develop an algorithm for the integration of a BESS into an intentional controlled islanding.

The final step involves evaluating the performance of the BESS during intentional controlled islanding. Each island undergoes a balance check during a failure scenario to assess the balance between load and generation power. If there is a power imbalance, the BESS will be required to obtain power balance on each island. This use of BESS demonstrates its effectiveness in achieving a balanced island, thereby fulfilling objective 3.

Successful balance across all islands concludes the process, affirming that BESS integration in the intentional controlled islanding algorithm maintains balanced states without resorting to load-shedding methods. This methodology systematically guides the evaluation of intentional islanding strategies, emphasizing BESS's role in achieving optimal island configurations. The accompanying flowchart visually represents these sequential steps, reinforcing the methodology's effectiveness in power system engineering.

3.3.1 Size of BESS Analysis

Figure 3.3 is a flowchart showing the process for analyzing load data for each island in the context of a intentional controlled islanding power system. This analysis is to prove that the percentage proposed for the size of BESS based on the total load in the system network is appropriate to use. The data obtained from previous studies [47] and [48] is the basis for assessing the load on each island.

The process begins with the first step, which involves determining the load data by referring to previous papers [47] and [48] that use a load shedding scheme for intentional controlled islanding. Once the load data is obtained, determine the total load before forming island and the total load on each island after forming island in the system, with a focus on identifying the highest load on each island.

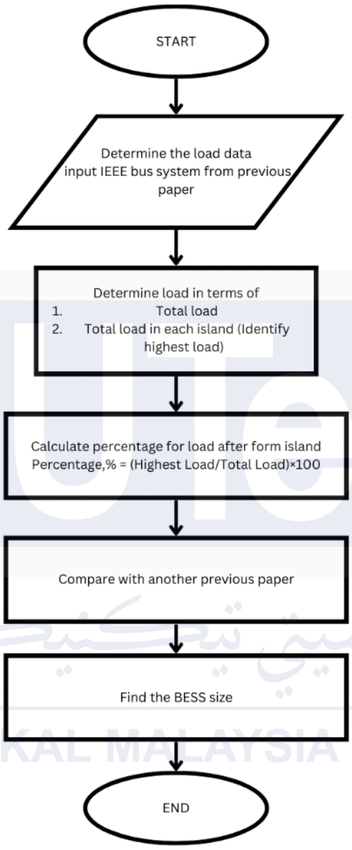

Figure 3.3: Flow Chart for Analysed the Size of BESS

After load identification, the next step is to calculate the load percentage after islanding. This calculation utilizes the formula provided in the flowchart. This calculation aims to assess the percentage of the highest total load on each island after island formation compared to the total load before islanding. Finally, the process concludes with a percentage comparison of the results obtained from the previous paper. This comparison aims to prove that the highest percentage from the analysis made from previous studies does not exceed the percentage that has been suggested.

This is because, when forming an island, the BESS will be able to support power for the entire load on the island if the power generation is less than the power load.

For the size of the BESS, the proposed size is 80% of the total load data. Previous studies were utilized to analyze both the total load data and the load data for each island, confirming the suitability of the proposed percentage for the BESS size. Data collection and analysis details according to [48] and [47] are presented in Table 3.1.

Table 3.1: Analysis Total Load from Previous Study

For IEEE-30 bus system				
Previous study	Island	Total load each island (MW)	Total load (MW)	Percent used (%)
[48]	Island 1	68.3	137.5	**50.3%**
	Island 2	69.2		
For IEEE-39 bus system				
Previous study	Island	Total load each island (MW)	Total load (MW)	Percent used (%)
[48]	Island 1	1455.5	6097.1	**38.9%**
	Island 2	2376.5		
	Island 3	2265.1		
For IEEE-30 bus system				
Previous study	Island	Total load each island (MW)	Total load (MW)	Percent used (%)
[47]	Island 1	170.4	283.4	**60.1%**
	Island 2	113.0		
For IEEE-39 bus system				
Previous study	Island	Total load each island (MW)	Total load (MW)	Percent used (%)
[47]	Island 1	4134.130	6254.23	**66.1%**
	Island 2	2120.100		

Based on the analysis above, it is proven that after dividing into islands, the percentage of load on each island does not exceed 80% of the total load when forming an island

3.3.2 Location of BESS Analysis

Flowchart Figure 3.4 represents a systematic approach to identify the most efficient location for a Battery Energy Storage System (BESS) within the IEEE bus system framework. The location of the BESS is determined by the bus with the lowest total line losses, as indicated in the literature review. The primary objective of determining the location of the BESS is to minimize power losses, and total line losses are a significant component of these power losses in a power system.

Figure 3.4: Flow Chart of Location of BESS

This process begins with the collection of load data, specifically the number of load buses. All data including bus, transmission line and generator values for this test system are obtained from [9]. With this information, the procedure proceeds to the simulation of adding BESS values to the load bus in the network. Following the simulation, the next step is to calculate the total line loss for the bus load when the BESS value is increased. Line loss is an important consideration because it represents the power lost during electricity transmission. After line losses are calculated, the process continues for each bus load in the system. This iterative process continues until all total line losses are calculated for each bus load

The final phase is choosing the optimal location for the BESS. This selection is made by identifying the load bus with the lowest line loss as the most suitable location for the BESS. After determining this optimal location, the process ends.This structured methodology is designed to optimize the placement of BESS in the power system, which ultimately aims to reduce line losses and improve overall system performance.

3.4 Integrate BESS into Intentional Islanding Solution

The process outlined in Figure 3.5 begins with the intentional controlled islanding solution derived from a previous case study [9], which employs the Modified Discrete Evolutionary Programming (MDEP) algorithm to develop an optimal intentional islanding strategy. This solution offers a planned approach to creating intentional islands within the power grid to prevent total blackouts.

The next crucial step is to conduct a load flow analysis. During this phase, a detailed load flow analysis is performed to assess the balance of power generation and demand within each island. This analysis is essential to understand the current state of power distribution across the network and to identify which islands are balanced and which are unbalanced.

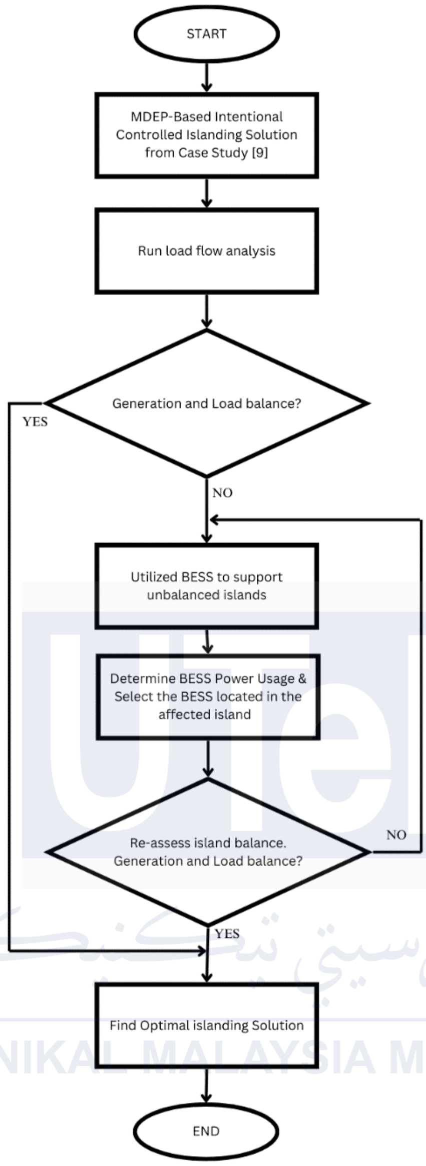

Figure 3.5: Flow Chart of Integrate BESS into intentional islanding solution

Once the load flow analysis is complete, the process proceeds to identifying unbalanced islands. If all islands are found to be balanced, the process is deemed successful, and no further action is required. However, if there are unbalanced islands where the generation does not match the load, further steps are necessary. At this stage, the Battery Energy Storage System (BESS) is utilized to address the imbalance.

The next action involves "Utilized BESS to support unbalanced islands." This step includes two sub-actions:

1. Select BESS for Deployment: The BESS units located within the affected islands are identified. If there are multiple units, the one that is strategically positioned to correct the imbalance is chosen.
2. Determine BESS Power Usage: The amount of power that needs to be supplied or absorbed by the BESS is calculated, based on the load and generation difference within the unbalanced island.

Following the deployment of the BESS, the process requires reassessment of island balance. Another load flow analysis is carried out to verify that the BESS deployment has successfully achieved balance in previously unbalanced islands. If balance is achieved, the optimal islanding with BESS is considered successful. However, if the islands remain unbalanced, further adjustments to the BESS deployment may be necessary.

The process culminates with the step to find the optimal islanding solution. This step confirms that an optimal configuration has been achieved where all islands operate with balanced load and generation, thus concluding the process successfully.

3.5 Chapter Summary

The proposed methodology for integrating Battery Energy Storage Systems (BESS) into intentional controlled islanding in power systems follows a systematic flow outlined in Figures 3.2, 3.3, 3.4 and 3.5. It initiates a power flow analysis of the IEEE test system to determine the total load, proceeds to ascertain optimal BESS size and location based on previous studies, and integrates BESS into an intentional controlled islanding algorithm. The methodology emphasizes evaluating BESS effectiveness in achieving balanced islands without resorting to load shedding. The size of BESS is analyzed by assessing load data for each island, validating the proposed BESS size against previous studies. Similarly, the optimal location of BESS is determined by minimizing total line losses in the IEEE bus system framework. The final phase involves integrating BESS into the intentional islanding solution, where load flow analysis is conducted, unbalanced islands are identified, and BESS is deployed strategically to support these islands. Re-assessment ensures the achievement of balanced islands, leading to the identification of an optimal islanding solution. The methodology provides a structured and sequential approach, offering valuable insights into the integration of BESS in intentional controlled islanding strategies for power systems. Further validation can be pursued through case studies in chapters 4.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter explores the results and discussion of the study on optimizing intentional controlled islanding with a Battery Energy Storage System (BESS), based on the methodology outlined in the previous section. The intentional controlled islanding solution derived from a previous case study [9], which employs the Modified Discrete Evolutionary Programming (MDEP) algorithm to develop an optimal intentional islanding algorithm. Six case studies using the IEEE 30-bus, IEEE 39-bus, and IEEE 118-bus system test systems are utilized for this purpose. The process begins by identifying the BESS parameters, which are the size and location of the BESS within each system test. Then, BESS integration in each system is analyzed to evaluate the effectiveness of BESS integration in achieving power balance during intentional islanding. The effectiveness of these algorithms lies in the ability of BESS to balance unbalanced islands. MATLAB 10 (R2015a) software was used for this work. All data, including bus, transmission line, and generator values for this test system, were obtained from [45] and [46].

4.2 BESS Parameter IEEE Test System

In this study, the IEEE 30-bus, IEEE 39-bus, and IEEE 118-bus systems were analyzed to determine the optimal size and location of Battery Energy Storage Systems (BESS). These findings were then applied to evaluate how effectively BESS can facilitate intentionally isolated power islands. To demonstrate the effectiveness of utilizing BESS in performing intentional controlled islanding, generator and load values were adjusted in each test system. Detailed data for generators and loads can be found in Appendix A (Tables A.1 to A.3).

4.2.1 IEEE 30-Bus Test System

The objective of this analysis is to identify the BESS's location and size for the IEEE 30-bus test system. The IEEE 30-bus test system consists of 6 generators, 24 load buses, and 41 transmission lines and the network diagram of the IEEE 30-bus test system is shown in Figure 4.1. The size and location of BESS have been determined by analysis, which will be covered in this discussion.

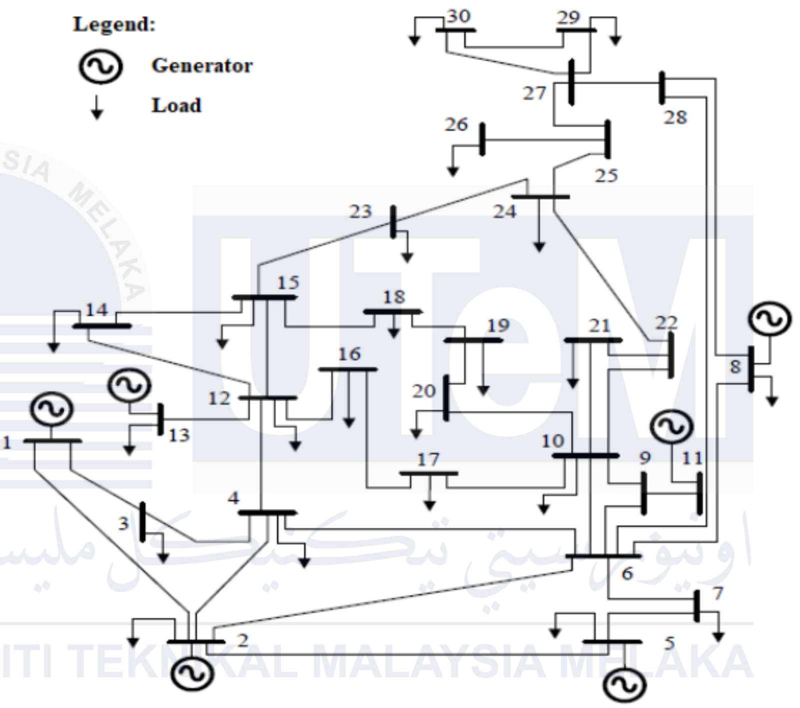

Figure 4.1: Schematic of the IEEE 30-Bus Test System

Table 4.1: BESS Parameter IEEE 30-bus Test System

Description	Remarks
Total Load	405.2MW
Power Required from BESS	325MW
Size of BESS	65MW/260MWh
Location of BESS	9, 27, 28, 29, and 30

The Newton-Raphson Method for Power Flow Analysis revealed that the total load for the IEEE 30-bus system amounts to 405.2MW. Through meticulous analysis, it has been demonstrated that when dividing the system into islands, the load on each island does not exceed 80% of the total load, ensuring efficient load management. Consequently, it is justified to adopt 80% of the total load as the standard for sizing Battery Energy Storage Systems (BESS), corroborated by previous studies. This standardization resulted in a BESS size calculation of 325MW, aligning with the suggested 80% total load utilization.

To implement the BESS, the system design proposed distributing the total BESS capacity across five units, each with a capacity of 65MW/260MWh. The selection of BESS size refers to the size of BESS that has been installed in Georgia which is 65MW/260MWh [49]. The placement strategy for these BESS units required a comprehensive analysis of line losses within the IEEE 30-bus system framework. Utilizing MATLAB simulations, each load bus was assessed for line losses with the integration of a 65MW BESS. All the results for the total losses in each bus are provided in Appendix A (Table A-4). The analysis identified bus 29 as having the lowest line loss of 28.870MW, indicating its suitability for BESS placement.

Based on the findings from the line loss analysis, it was concluded that the most optimal locations for the BESS units are buses 9, 27, 28, 29, and 30, as these buses exhibited lower line losses. This strategic placement is expected to enhance the efficiency and reliability of the power system, minimizing energy losses while effectively managing the load. The implementation of these recommendations is poised to optimize the performance of the IEEE 30-bus system, ensuring a balanced and resilient energy distribution network.

4.2.2 IEEE 39-Bus Test System

The objective of this analysis is to identify the BESS's location and size for the IEEE 39-bus test system. The IEEE 39-bus test system consists of 10 generators, 29 load buses, and 46 transmission lines and the network diagram of the IEEE 30-bus test system is shown in Figure 4.2.

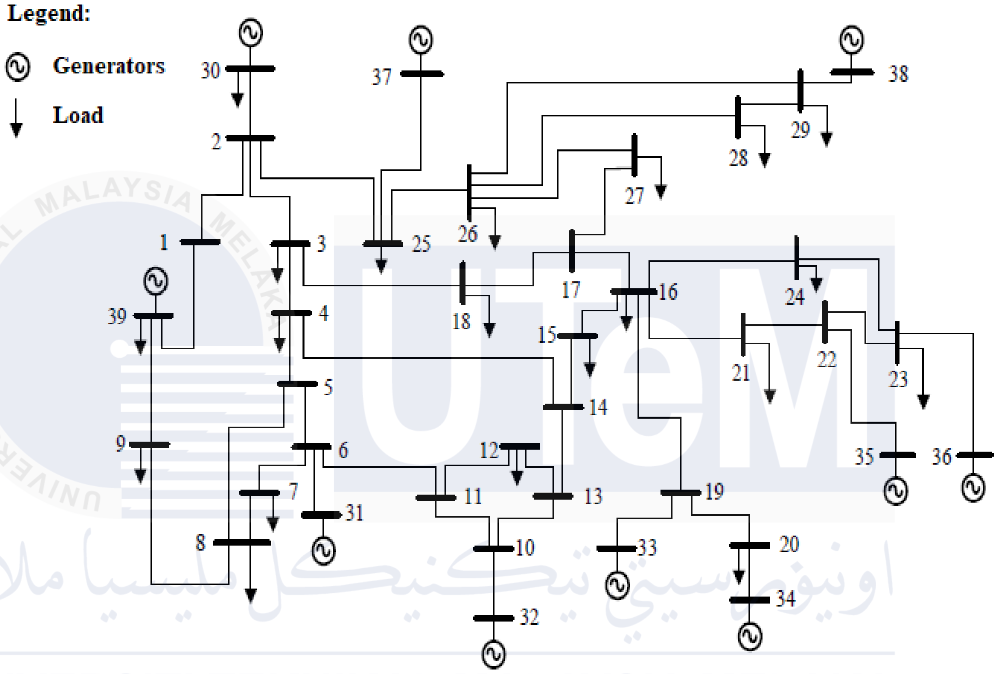

Figure 4.2: Schematic of the IEEE 39-Bus Test System

Table 4.2: BESS Parameter IEEE 39-bus Test System

Description	Remarks
Total Load	6806.730MW
Power Required from BESS	5500MW
Size of BESS	300MW/1200MWh
Location of BESS (Bus)	1, 2, 3, 4, 5, 6, 7, 8, 9, 14, 15, 16, 17, 18, 21, 23, 24, and 27

The Power Flow Analysis using the Newton-Raphson Method shows that the total load for the IEEE 39-bus system amounts to 6806.730MW. In line with the methodology, the proposed size for the Battery Energy Storage System (BESS) is calculated as 80% of this total load. Consequently, the BESS size is determined to be 5500MW. This proposed capacity is to be distributed across 18 BESS units, each with a capacity of 300MW/1200MWh, which aligns with the highest capacity of BESS currently recorded [35]. The large number of BESS sets is due to the large load value and the maximum capacity value of BESS ever recorded is only 300MW.

Identifying optimal locations for the BESS placement necessitates a detailed line losses analysis within the IEEE bus system framework. MATLAB simulations were used to add a 300MW BESS to each load bus in the network, with the aim of calculating the line losses associated with the inclusion of the BESS. The line loss analysis results, presented in Appendix A (A-5), identified bus 8 as having the lowest line loss of 43.463MW.

Based on the line loss analysis, it is recommended that BESS units be placed at buses 1, 2, 3, 4, 5, 6, 7, 8, 9, 14, 15, 16, 17, 18, 21, 23, 24, and 27 due to their lower line losses. It is expected that by reducing energy losses and efficiently maintaining the load, this strategic placement would improve the power system's efficiency. Implementing these recommendations will optimize the performance of the IEEE 39-bus system, ensuring a balanced and resilient energy distribution network.

4.2.3 IEEE 118-Bus Test System

The objective of this analysis is to identify the BESS's location and size for the IEEE 118-bus test system. The IEEE 118-bus test system consists of 19 generators, 99 load buses, and 186 transmission lines and the network diagram of the IEEE 118-bus test system is shown in Figure xx.

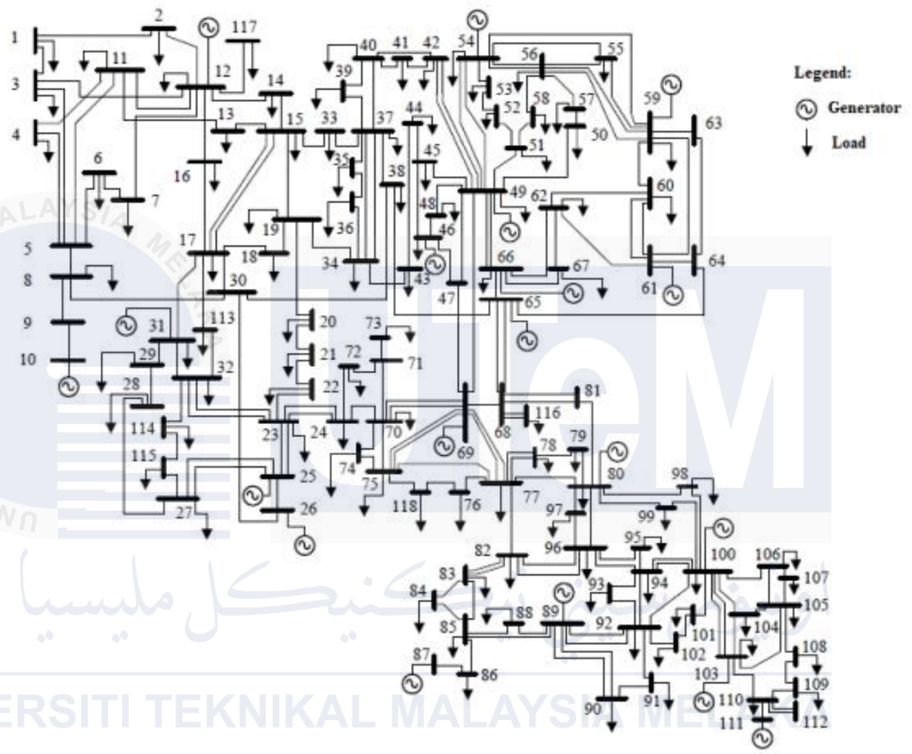

Figure 4.3: Schematic of the IEEE 118-Bus Test System

Table 4.3: BESS Parameter IEEE 118-bus Test System

Description	Remarks
Total Load	5071MW
Power Required from BESS	4200MW
Size of BESS	300MW/1200MWh
Location of BESS	82, 84, 85, 86, 88, 92, 93, 94, 95, 96, 97, 101, and 102

The Power Flow Analysis using the Newton-Raphson Method reveals that the total load for the IEEE 118-bus system amounts to 5071MW. Based on the analysis, the required Battery Energy Storage System (BESS) size is determined as 80% of the total load, resulting in a BESS capacity of 4200MW. To distribute this capacity, it is proposed to install 14 BESS units, each with a capacity of 300MW/1200MWh, aligning with the highest recorded capacity of BESS currently available [35].

To determine the optimal locations for BESS placement, a comprehensive line losses analysis was conducted within the IEEE bus system framework. Using the collected load data, MATLAB simulations were performed to add a 300MW BESS to each load bus in the network, calculating the line losses incurred with the inclusion of the BESS. The results of the line loss analysis, presented in Appendix A (A-6), identified bus 82 as having the lowest line loss of 43.463MW.

Based on the findings, it is recommended that BESS units be placed at buses 82, 84, 85, 86, 88, 92, 93, 94, 95, 96, 97, 101, and 102, as these buses exhibited the lowest line losses. This strategic placement is expected to enhance the efficiency and reliability of the power system by minimizing energy losses and optimizing load management. Implementing these recommendations will optimize the performance of the IEEE 118-bus system, ensuring a balanced and resilient energy distribution network.

4.3 Analysis of the IEEE 30-bus system

Two case studies were conducted using the IEEE 30-bus test system to demonstrate the effectiveness of utilizing BESS in performing intentional controlled islanding. The results, including the values of the generator buses, line losses, power imbalance, and BESS deployment, illustrate the system's performance during intentional controlled islanding. The optimal intentional controlled islanding algorithm was obtain based on the previous work reported in [9].

4.3.1 Case study 1

In Case Study 1, intentional controlled islanding was executed by splitting the system into two islands based on the coherent groups of generators: G1 = {1, 2, 5, 13} and G2 = {8, 11}. As shown in Figure 4.4, the optimal intentional controlled islanding strategy (cutsets) for Case Study 1 was determined to be 2–6, 4–6, 5–7, 16–17, 18–19, and 23–24. The Battery Energy Storage System (BESS) has been set to be on bus 9, 27, 28, 29 and 30, each with a maximum capacity of 65MW/260MWh.

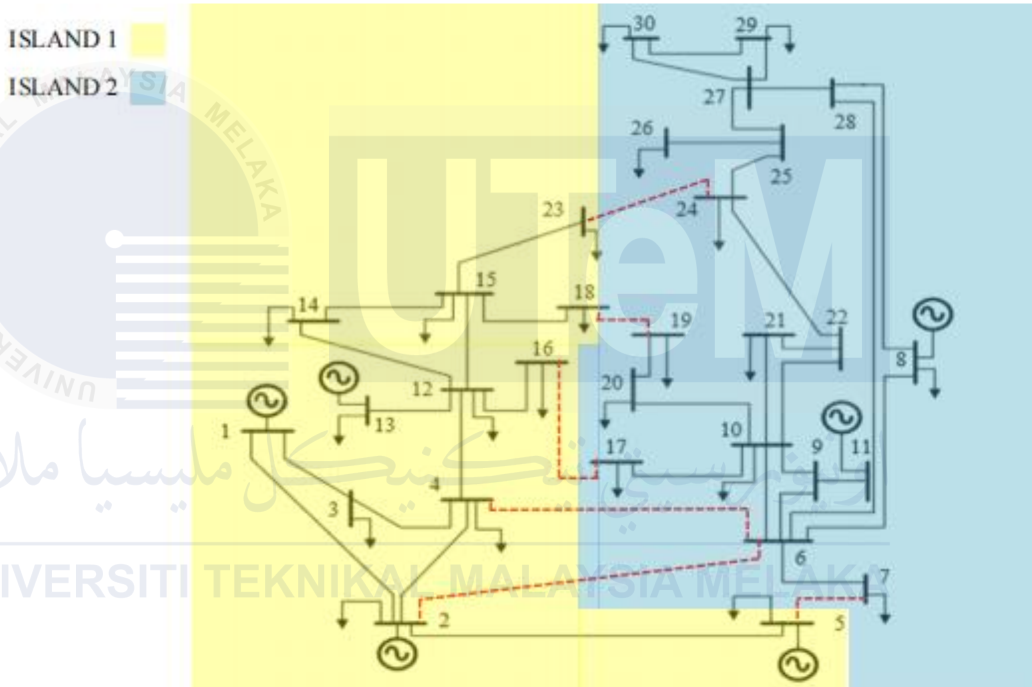

Figure 4.4: One-Line Diagram for Case Study 1 Before Integrating BESS

Table 4.4: Results for Before and After Intentional Islanding Equipped with BESS for Case Study 1

Island 1	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info: 1–5, 12–16, 18, 23	*G_1	360	260.998	129.018
	G_2	140	40	40
	G_5	100	0	0
	G_{13}	100	0	0
	Total generated power, P_{gen} (MW)		300.998	169.018
	Total load, P_{load} (MW)		161.4	161.4
	Total power loss, P_{loss} (MW)		25.633	7.618
	Total power imbalance, P_{imb} (MW)		113.965	0

Island 2 Buses info: 6–11, 17, 19–22, 24–30	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
	*G_8	100	0	95.407
	G_{11}	100	0	100
	B_9	65	-	12.40
	B_{27}	65	-	0
	B_{28}	65	-	0
	B_{29}	65	-	0
	B_{30}	65	-	0
	Total generated power, P_{gen} (MW)		0	207.807
	Total load, P_{load} (MW)		206.2	206.2
	Total power loss, P_{loss} (MW)		1.357	1.610
	Total power imbalance, P_{imb} (MW)		-207.557	0

Slack bus

The Table 4.2 present the total generated power (P_{gen}), total load (P_{load}), total power loss (P_{loss}), and total power imbalance (P_{imb}) before and after intentional islanding for both Island 1 and Island 2, which is labeled as 'pre-islanding' and 'post-islanding'. In Island 1, before islanding, there was an power surpluss of 113.965 MW, mainly due to high power generation at the slack bus G_1. After islanding, adjustments were made through load flow analysis to restore power balance. G_1 reduced its power generation from 260.998 MW to 128.299 MW to ensure equilibrium within the island, thus eliminating the need for the Battery Energy Storage System (BESS) and allowing Island 1 to operate independently as a balance island.

In Island 2, a power deficit of 207.557 MW was observed due to the absence of a slack bus, which was originally located in Island 1. Therefore, a new slack bus, G_8, was designated in Island 2 based on its maximum power limit. Despite this, the available power from G_8 and G_{11} was insufficient to meet the load demand because the total of maximum capacity G_8 and G_{11} is 200MW, while the load demand is 206.2MW, there is a power deficit of 6.2MW. Consequently, the BESS situated at bus 9 was necessary to provide additional power support, the power support required from the BESS needs to be doubled to consider the line loss that will occur, resulting in a total generated power of 12.4 MW from the BESS. Ultimately, the power balance criteria were achieved for Island 2, as detailed in the

Table 4.2. From the total power generated by BESS, the duration that the BESS can support the system is 21 hours. This duration are calculated by dividing the capacity in MWh by the rated power in MW. Figure 4.5 present the one-line diagram for Case Study 1 after the integration of a Battery Energy Storage System (BESS), highlighting the location of the BESS necessary in the IEEE 30-bus system to achieve power balance during intentional islanding.

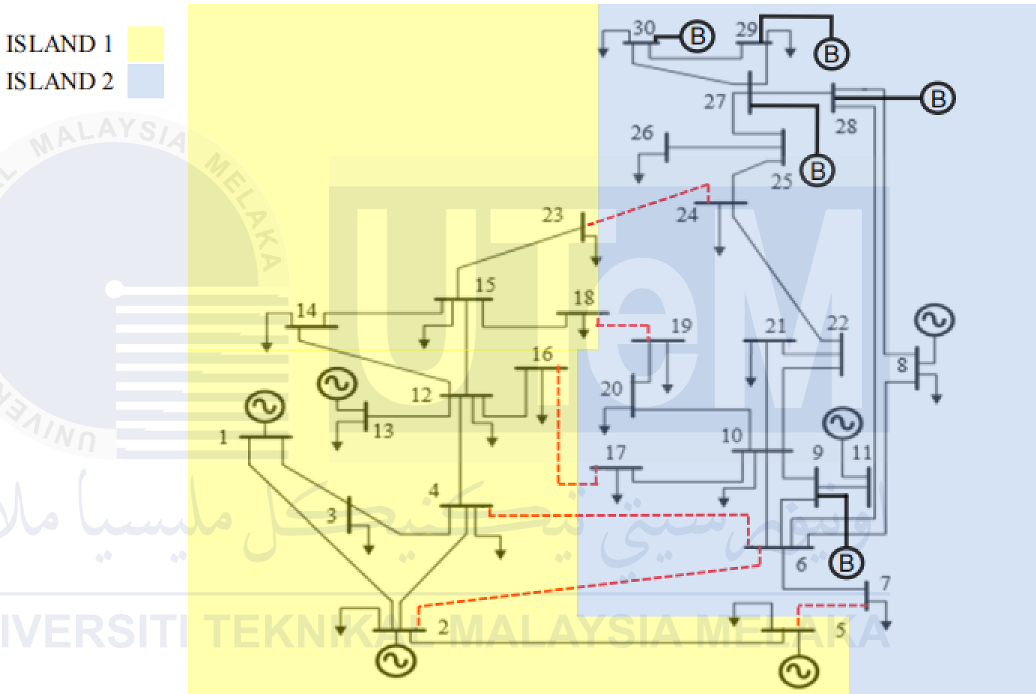

Figure 4.5: One-Line Diagram for Case Study 1 After Integrating BESS

4.3.2 Case study 2

For Case Study 2, a different set of coherent groups of generators was investigated using the IEEE 30-bus test system. The system was partitioned into three islands based on the coherent groups of generators: G1 = {1, 2, 5, 13}, G2 = {8}, and G3 = {11}. The optimal intentional controlled islanding strategy (cutsets) for this case study was 2–6, 4–6, 5–7, 6–9, 6–10, 16–17, 18–19, 23–24, and 24–25. The Battery Energy Storage System (BESS) has been set to be on buses 9, 27, 28, 29 and 30, each with a capacity of 65MW/260MWh.

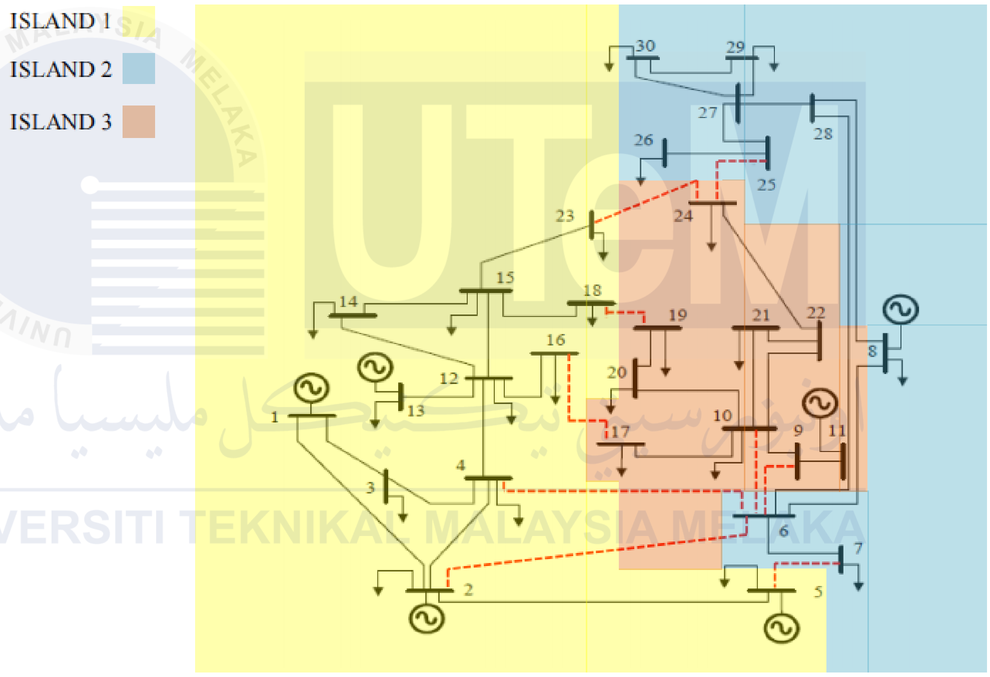

Figure 4.6: One-Line Diagram for Case Study 2 Before Integrating BESS

Table 4.5: Results for Before and After Intentional Islanding Equipped with BESS for Case Study 2

Island 1	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info: 1–5, 12–16, 18, 23	*G_1	360	260.998	128.0.75
	G_2	140	40	40
	G_5	100	0	0
	G_{13}	100	0	0
	Total generated power, P_{gen} (MW)		300.998	168.0.75
	Total load, P_{load} (MW)		161.4	161.4
	Total power loss, P_{loss} (MW)		19.159	6.675
	Total power imbalance, P_{imb} (MW)		120.439	0

Island 2	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info: 6–8, 25–30	*G_8	100	0	98.256
	B_{27}	65	-	13.8
	B_{28}	65	-	0
	B_{29}	65	-	0
	B_{30}	65	-	0
	Total generated power, P_{gen} (MW)		0	112.056
	Total load, P_{load} (MW)		106.9	106.9
	Total power loss, P_{loss} (MW)		6.172	5.156
	Total power imbalance, P_{imb} (MW)		-113.072	0

Island 3	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info: 9–11, 17, 19–22, 24	*G_{11}	100	0	53.189
	B_9	65	-	0
	Total generated power, P_{gen} (MW)		0	53.189
	Total load, P_{load} (MW)		52.7	52.7
	Total power loss, P_{loss} (MW)		0.679	0.489
	Total power imbalance, P_{imb} (MW)		-53.379	0

***Slack bus**

In Island 1, there was a power surplus of 120.439 MW before islanding, mainly due to high power generation from the slack bus G_1. After islanding, load flow analysis was performed to adjust the system parameters. Post-islanding, G_1 reduced its power generation from 260.998 MW to 128.075 MW to maintain power balance within the island. This adjustment met the power balance criterion, removing the need for the BESS and allowing Island 1 to operate independently as a balanced island.

In Island 2, there was a power deficit of 113.072 MW, mainly due to the absence of a slack bus, as the original slack bus was in Island 1. Thus, a new slack bus had to be designated in Island 2. Generator bus G_8 was selected based on its highest maximum power limit among the available generator (PV) buses. Before islanding, the total power generated (P_{gen}) in this island was 0.000 MW, while the total load (P_{load}) was 106.9 MW. However, the maximum power limit for G_8 was 100 MW, which was insufficient to meet the load demand because there is a power deficit of 6.9MW. Consequently, the BESS at bus 27, B_{27} was required. The BESS provided additional power support, contributing 13.8 MW to the total generated power (Pgen) because to consider the line loss that will occur. As a result, the power balance criterion was satisfied for Island 2, as shown in the Table 4.3. From the total power generated by BESS, the duration that the BESS can support the system is 18.8 hours. This duration can be calculated by dividing the capacity in MWh by the rated power in MW. Figure 4.7 present the one-line diagram for Case Study 2 after the integration of a Battery Energy Storage System (BESS), highlighting the location of the BESS necessary in the IEEE 30-bus system to achieve power balance during intentional islanding.

In Island 3, there was a power deficit of 53.379 MW due to the absence of a slack bus, with the original slack bus in Island 1. Generator bus G_{11} was selected as the slack bus. Before islanding, the total power generated (Pgen) in this island was 0.000 MW, while the total load demand was 52.7 MW. However, the maximum power limit for G_{11} was 100 MW, which was sufficient to cover the load demand. After islanding, G_{11} increased its power generation from 0 MW to 53.189 MW to maintain power balance within the island. This adjustment met the power balance criterion, eliminating the need for BESS and allowing Island 3 to to operate independently as a balanced island.

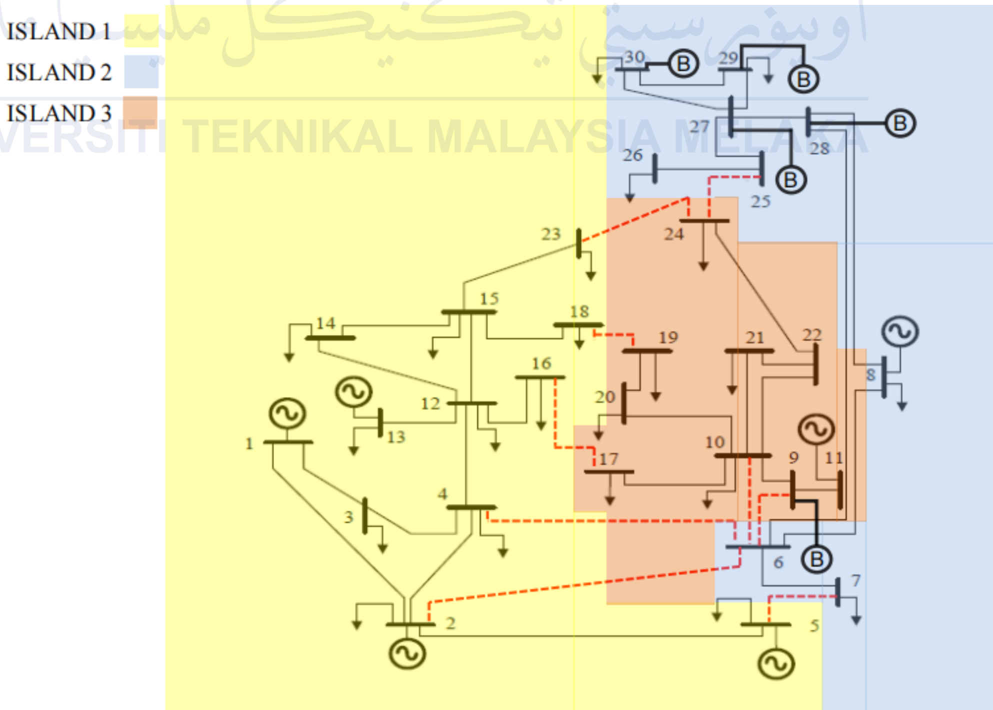

Figure 4.7: One-Line Diagram for Case Study 2 After Integrating BESS

4.4 Analysis of the IEEE 39-bus system

Two case studies were carried out using the IEEE 39-bus test system to demonstrate the effectiveness of utilizing BESS in performing intentional controlled islanding. The results, including the values of the generator buses, line losses, power imbalance, and BESS deployment, illustrate the system's performance during intentional controlled islanding. The optimal intentional controlled islanding algorithm was obtain based on previous works reported in [9].

4.4.1 Case study 3

For Case Study 3, the system was partitioned into two islands based on the coherent groups of generators: G1 = {30, 31, 32, 37, 38, 39} and G2 = {33, 34, 35, 36}. The optimal intentional controlled islanding strategy (cutsets) for this case study was 3–18, 14–15, and 17–27. The Battery Energy Storage System (BESS) has been set to be on buses 1, 2, 3, 4, 5, 6, 7, 8, 9, 14, 15, 16, 17, 18, 21, 23, 24, and 27, each with a capacity of 300MW/1200MWh.

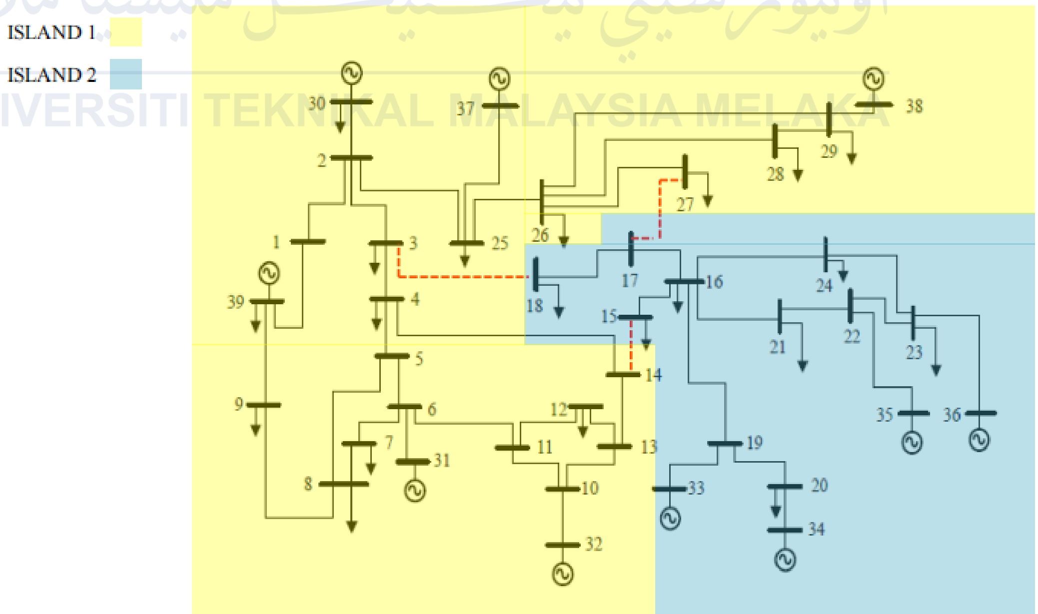

Figure 4.8: One-Line Diagram for Case Study 3 Before Integrating BESS

Table 4.6: Results for Before and After Intentional Islanding Equipped with BESS for Case Study 3

Island 1	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info:	G_{30}	1040	650	650
1–14, 25–32,	$*G_{31}$	646	632.837	223.212
37–39	G_{32}	752	750	750
	G_{37}	564	560	560
	G_{38}	865	860	860
	G_{39}	1100	1060	1060
	B_1	300	-	0
	B_2	300	-	0
	B_3	300	-	0
	B_4	300	-	0
	B_5	300	-	0
	B_6	300	-	0
	B_7	300	-	0
	B_8	300	-	0
	B_9	300	-	0
	B_{14}	300	-	0
	Total generated power, P_{gen} (MW)		4481.817	4073.212
	Total load, P_{load} (MW)		4037.130	4037.130
	Total power loss, P_{loss} (MW)		30.476	36.082
	Total power imbalance, P_{imb} (MW)		414.211	0

Island 2	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info:	G_{33}	652	632	632
15–24, 33–36	G_{34}	508	508	508
	$*G_{35}$	687	650	376.817
	G_{36}	580	580	580
	B_{15}	300	-	300
	B_{16}	300	-	300
	B_{17}	300	-	85.2
	B_{18}	300	-	0
	B_{21}	300	-	0
	B_{23}	300	-	0
	B_{24}	300	-	0
	B_{27}	300	-	0
	Total generated power, P_{gen} (MW)		2370	2782.017
	Total load, P_{load} (MW)		2769.6	2769.6
	Total power loss, P_{loss} (MW)		13.64	12.419
	Total power imbalance, P_{imb} (MW)		-413.24	0

***Slack bus**

In Island 1, before islanding, there was a power surplus of 414.211 MW, mainly due to high power generation at the slack bus G_{31}. After islanding, load flow analysis was done to balance the system. G_{31} reduced its power generation from 632.873 MW to 223.242 MW to balance the island, eliminating the need for the Battery Energy Storage System (BESS) and allowing Island 1 to operate independently as a balanced island.

In Island 2, a power deficit of 413.24 MW occurred because there was no slack bus, which was originally in Island 1. A new slack bus, G_{35}, was chosen for Island 2 based on its maximum power capacity. However, the combined maximum power capacity of G_{33}, G_{34}, G_{35}, and G_{36}, totaling 2427 MW, was not enough to meet the load demand of 2769.6 MW, resulting in a power deficit of 342.6 MW. Therefore, BESS units at buses 15, 16, and 17 were needed to provide extra power. The required power support from the BESS needs to be doubled, resulting in up to 685.2 MW to account for the line loss that will occur and leave the slack bus that balances the system. This allowed Island 2 to meet the power balance criteria, as shown in the table. From the total power generated by the BESS, the duration that the BESS can support the system is 5.25 hours. Figure 4.9 present the one-line diagram for Case Study 3 after the integration of a Battery Energy Storage System (BESS), highlighting the location of the BESS necessary in the IEEE 39-bus system to achieve power balance during intentional controlled islanding.

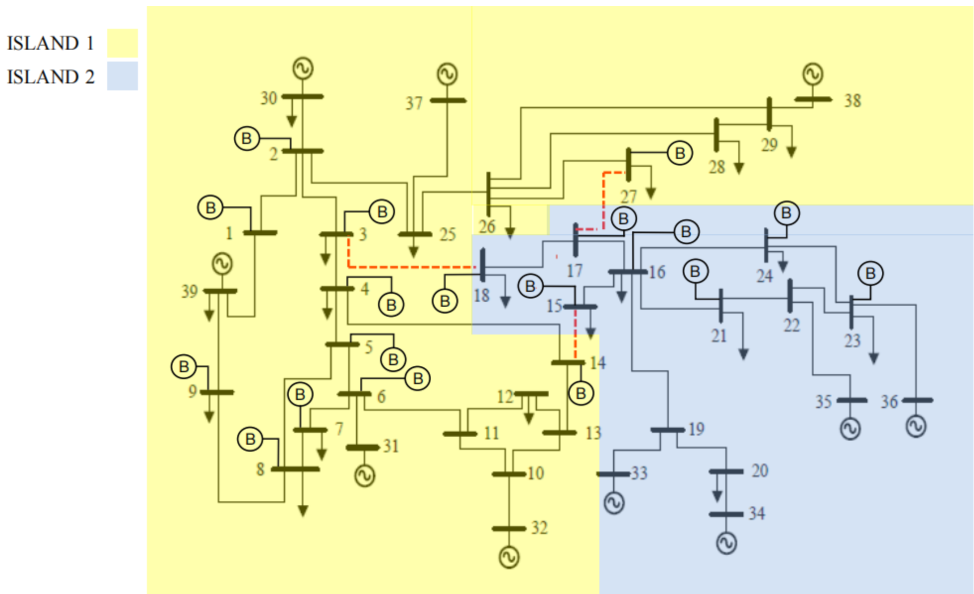

Figure 4.9: One-Line Diagram for Case Study 3 After Integrating BESS

4.4.2 Case Study 4

In Case Study 4, the system was partitioned into three islands based on the coherent groups of generators: G1 = {30, 37, 38}, G2 = {31, 32, 39}, and G3 = {33, 34, 35, 36}. The optimal intentional controlled islanding strategy for this case was 1–39, 3–4, 3–18, 14–15 and 17–27. The Battery Energy Storage System (BESS) has been set to be on buses 1, 2, 3, 4, 5, 6, 7, 8, 9, 14, 15, 16, 17, 18, 21, 23, 24, and 27, each with a capacity of 300MW/1200MWh.

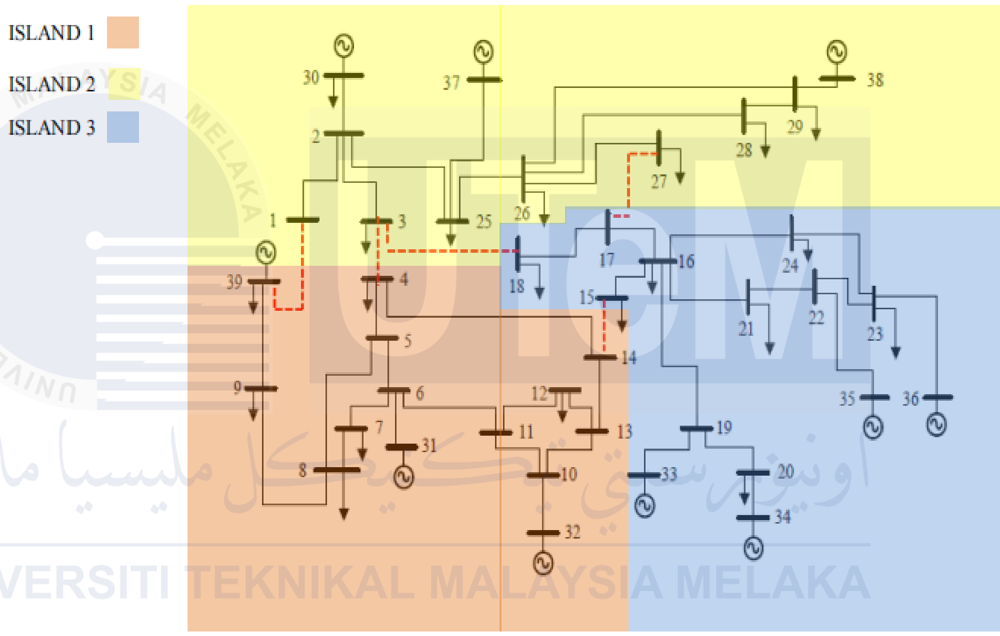

Figure 4.10: One-Line Diagram for Case Study 4 Before Integrating BESS

Table 4.7: Results for Before and After Intentional Islanding Equipped with BESS for Case Study 4

Island 1 Buses info: 4–14, 31–32, 39	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
	*G_{31}	646	632.837	645.305
	G_{32}	725	720	723.000
	G_{39}	1100	1060	1098.000
	B_4	300	-	26.060
	B_5	300	-	0
	B_6	300	-	0
	B_7	300	-	0
	B_8	300	-	0
	B_9	300	-	0
	B_{14}	300	-	0

	Total generated power, P_{gen} (MW)		2412.837	2492.365
	Total load, P_{load} (MW)		2484.03	2484.03
	Total power loss, P_{loss} (MW)		7.471	8.334
	Total power imbalance, P_{imb} (MW)		-78.664	0

Island 2	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info: 1–3, 25–30, 37–38	G_{30}	1040	650	650
	G_{37}	564	560	560
	*G_{38}	865	860	364.761
	B_1	300	-	0
	B_2	300	-	0
	B_3	300	-	0
	B_{27}	300	-	0
	Total generated power, P_{gen} (MW)		2070	1574.761
	Total load, P_{load} (MW)		1553.1	1553.1
	Total power loss, P_{loss} (MW)		23.289	21.661
	Total power imbalance, P_{imb} (MW)		493.611	0

Island 3	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info: 15–24, 33–36	G_{33}	652	632	632
	G_{34}	508	508	508
	*G_{35}	687	650	376.817
	G_{36}	580	580	580
	B_{15}	300	-	300
	B_{16}	300	-	300
	B_{17}	300	-	85.2
	B_{18}	300	-	0
	B_{21}	300	-	0
	B_{23}	300	-	0
	B_{24}	300	-	0
	Total generated power, P_{gen} (MW)		2370	2782.017
	Total load, P_{load} (MW)		2769.6	2769.6
	Total power loss, P_{loss} (MW)		13.64	12.419
	Total power imbalance, P_{imb} (MW)		-413.24	0

Slack bus

In Island 1, there was a power deficit of 78.664 MW before intentional controlled islanding. After islanding, load flow analysis was performed to adjust the system parameters. It was found that the total power of all the generators was not enough to compensate for the power deficit because the total maximum power was 2471 MW while the total load demand was 2484.03 MW. Consequently, the BESS at bus 15, B_{15} was required. After islanding, the power generated by each generator increased, prioritizing the generators before using the power support from BESS. The

BESS provided additional power support, contributing 26.06 MW to the total generated power, P_{gen}. As a result, the power balance criterion was satisfied for Island 1, as shown in the Table 4.5. From the total power generated by the BESS, the duration that the BESS can support the system is 46 hours.

In Island 2, there was a power surplus of 113.072 MW before islanding. There was no slack bus in this island, so a new slack bus had to be designated. Generator bus G38 was selected based on its highest maximum power limit among the available generator (PV) buses. After islanding, load flow analysis was done to balance the system. G38 reduced its power generation from 860 MW to 364.761 MW to balance the island, removing the need for the Battery Energy Storage System, BESS and allowing Island 2 to operate independently as a balanced island.

In Island 3, there was a power deficit of 413.24 MW before islanding. With the original slack bus in Island 1, generator bus G_{35} was selected as the slack bus based on its highest maximum power limit among the available generator PV buses. Because the total maximum power of all generators was not able to compensate for the power deficit, the BESS at buses 15, 16, and 17 was required to provide extra power, adding up to 685.2 MW. The required power support from the BESS needs to be doubled to account for the line loss that will occur and leave the slack bus balances the system. This allowed Island 3 to meet the power balance criteria. From the total power generated by the BESS, the duration that the BESS can support the system is 5.25 hours. Figure 4.11 present the one-line diagram for Case Study 4 after the integration of a Battery Energy Storage System (BESS), highlighting the location of the BESS necessary in the IEEE 39-bus system to achieve power balance during intentional controlled islanding.

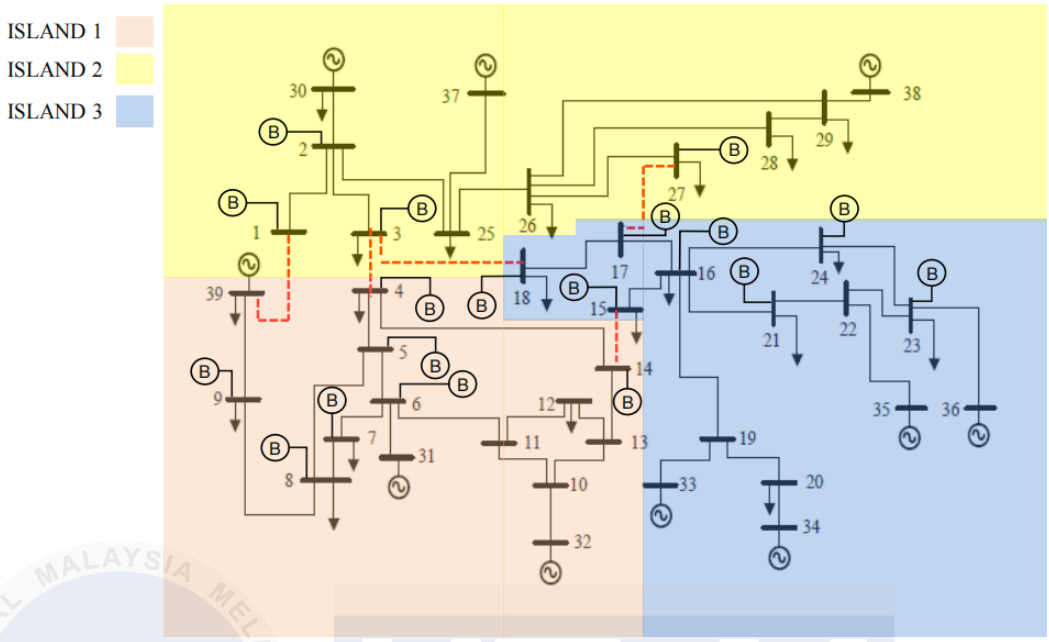

Figure 4.11: One-Line Diagram for Case Study 4 After Integrating BESS

4.5 Analysis of the IEEE 118-bus system

Two case studies were carried out using the IEEE 118-bus test system to demonstrate the effectiveness of utilizing BESS in performing intentional controlled islanding. The results, including the values of the generator buses, line losses, power imbalance, and BESS deployment, illustrate the system's performance during intentional controlled islanding. The optimal intentional controlled islanding algorithm was obtain based on previous works reported in [9].

4.5.1 Case study 5

For Case Study 5, the optimal intentional controlled islanding strategy was analyzed based on previously published works [23]. In this case study, the system was split into two islands based on the coherent groups of generators: G1 = {10, 12, 25, 26, 31, 46, 49, 54, 59, 61, 65, 66, 69, 80} and G2 = {87, 89, 100, 103, 111}. The optimal intentional controlled islanding strategy for this case study was 82–83, 94–96, 80–99, 95–96, and 98–100. The Battery Energy Storage System (BESS) has been set to be on buses 82, 84, 85, 86, 88, 92, 93, 94, 95, 96, 97, 101, and 102, each with a capacity of 300MW/1200MWh.

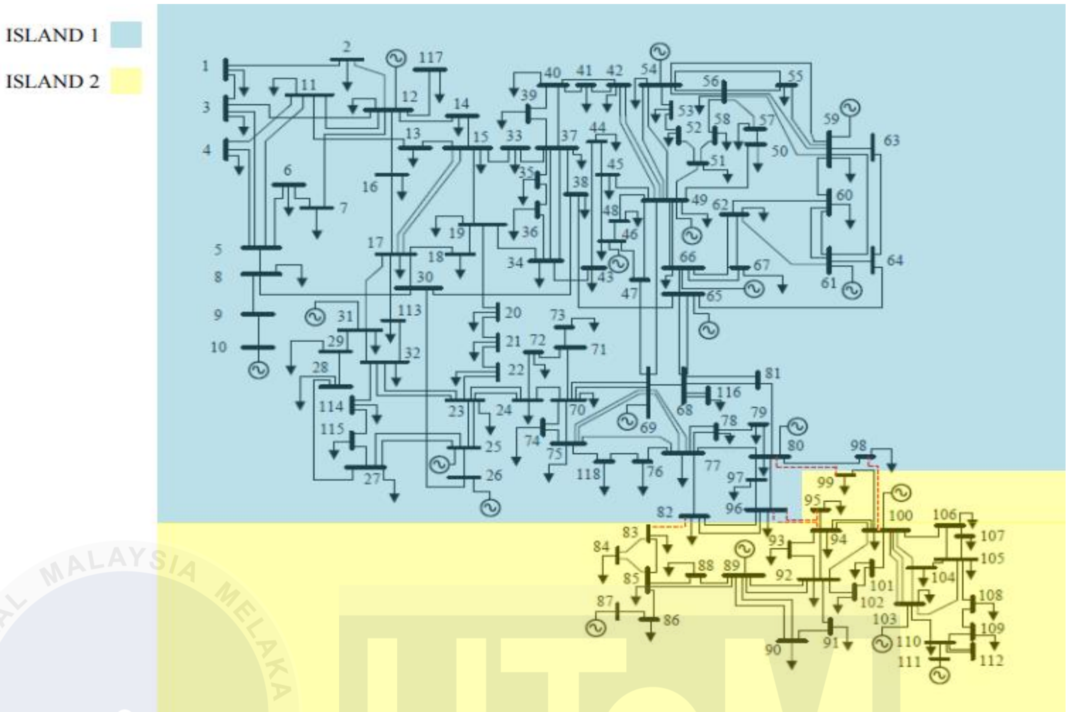

Figure 4.12: One-Line Diagram for Case Study 5 Before Integrating BESS

Table 4.8: Results for Before and After Intentional Islanding Equipped with BESS for Case Study 5

Island 1	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info: 1–82, 96–98, 113– 118	G_{10}	550	450	450
	G_{12}	185	85	85
	G_{25}	320	220	220
	G_{26}	414	314	314
	G_{31}	107	7	7
	G_{46}	119	19	19
	G_{49}	304	204	204
	G_{54}	148	148	148
	G_{59}	255	200	200
	G_{61}	260	200	200
	G_{65}	491	391	391
	G_{66}	492	392	392
	*G_{69}	805.2	662.346	321.758
	G_{80}	577	550	550
	B_{82}	300	-	0
	B_{96}	300	-	0
	B_{97}	300	-	0
	Total generated power, P_{gen} (MW)		3842.346	3501.758
	Total load, P_{load} (MW)		3396	3396
	Total power loss, P_{loss} (MW)		143.714	105.758
	Total power imbalance, P_{imb} (MW)		303.346	0

Island 2	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info: 83–95, 99–112	G_{87}	104	104	104
	$^*G_{89}$	707	700	566.402
	G_{100}	352	350	350
	G_{103}	140	140	140
	G_{111}	136	130	130
	B_{84}	300	-	300
	B_{85}	300	-	172
	B_{86}	300	-	0
	B_{88}	300	-	0
	B_{92}	300	-	0
	B_{93}	300	-	0
	B_{94}	300	-	0
	B_{95}	300	-	0
	B_{101}	300	-	0
	B_{102}	300	-	0
	Total generated power, P_{gen} (MW)		1424	1762.402
	Total load, P_{load} (MW)		1675	1675
	Total power loss, P_{loss} (MW)		51.632	87.419
	Total power imbalance, P_{imb} (MW)		-302.632	0

***Slack bus**

In Island 1, there was a power surplus of 303.346MW before intentional controlled islanding. The slack bus, G_{69}, was in Island 1. Load flow analysis was performed to obtain the new system parameters in the island. The results showed that G_{69} reduced its generated power from 662.346 MW to 321.758 MW to eliminate the power surplus in the island. Finally, the power balance criterion in Island 1 was met, eliminating the need for the Battery Energy Storage System (BESS).

In Island 2, a power deficit of 302.632MW occurred because there was no slack bus, which was originally in Island 1. A new slack bus, G_{89}, was chosen for Island 2 based on its highest power capacity. However, the combined maximum power capacity of all generators, totaling 1439 MW, was not enough to meet the load demand of 1675 MW, resulting in a power deficit of 236MW. Therefore, BESS at buses 84 and 85 was needed to provide extra power, adding up to 472 MW. The required power support from the BESS needs to be doubled, resulting in up to 472MW to account for the line loss that will occur and leave the slack bus that balances the system. Finally, this allowed Island 2 to meet the power balance criteria, as shown in the Table 4.6. From the total power generated by the BESS, the duration that the BESS can support the system is 5 hours. Figure 4.13 present the one-line diagram for Case Study 5 after the integration of a Battery Energy Storage System (BESS), highlighting the location of the BESS necessary in the IEEE 118-bus system to achieve power balance during intentional controlled islanding.

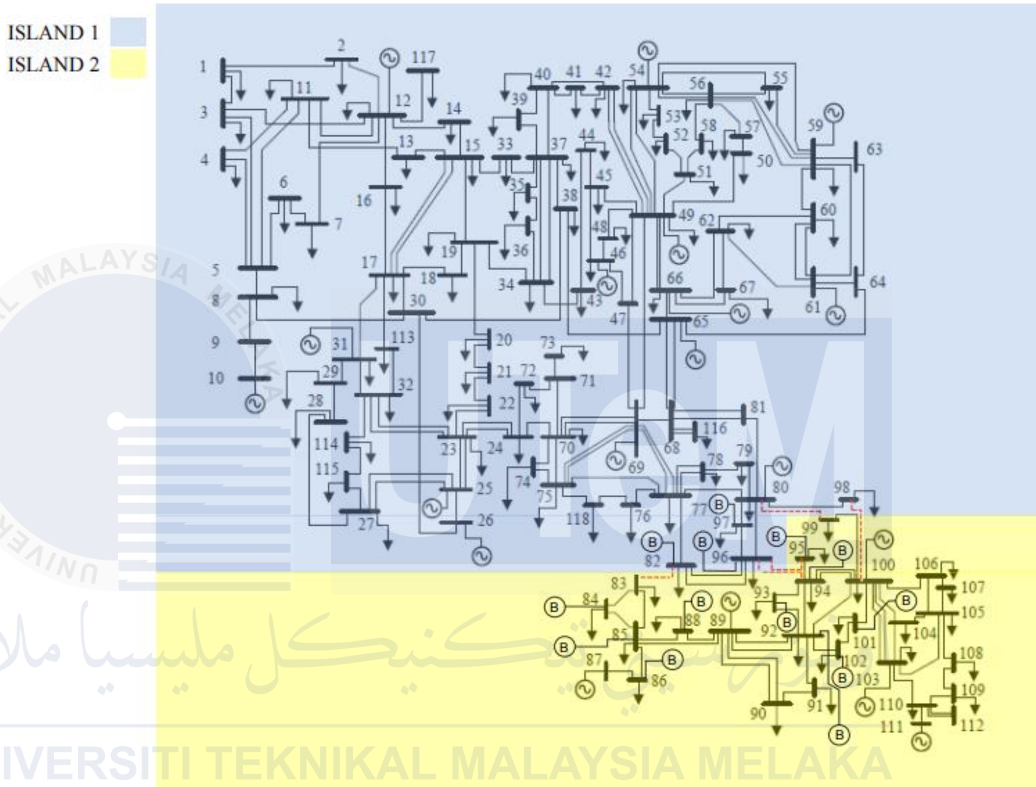

Figure 4.13: One-Line Diagram for Case Study 5 After Integrating BESS

4.5.2 Case study 6

For Case Study 6, the optimal intentional controlled islanding strategy was analysed based on a previous work [92]. In this case study, the system was partitioned into three islands based on the coherent groups of generators: G1 = {10, 12, 25, 26, 31}, G2 = {46, 49, 54, 59, 61, 65, 66, 69}, and G3 = {80, 87, 89, 100, 103, 111}. The optimal intentional islanding strategy for this case study was 15–33, 19–34, 30–38, 24–70, 24–72, 78–79, 77–80, 77–80, 68–81, and 77–82. The Battery Energy Storage System (BESS) has been set to be on buses 82, 84, 85, 86, 88, 92, 93, 94, 95, 96, 97, 101, and 102, each with a capacity of 300MW/1200MWh.

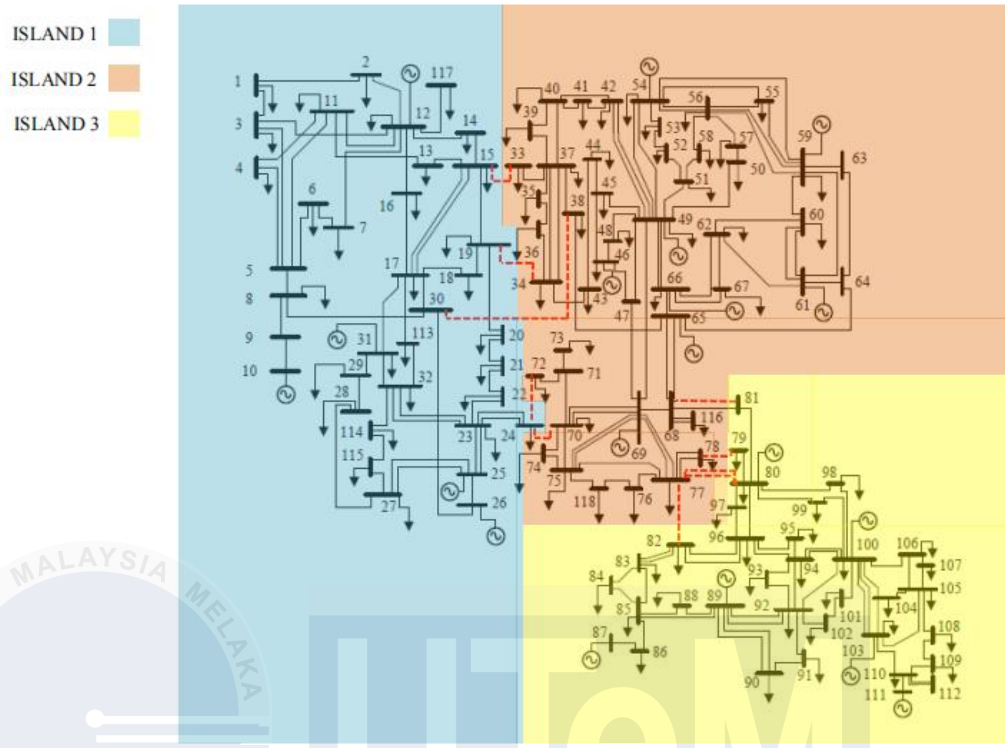

Figure 4.14: One-Line Diagram for Case Study 6 Before Integrating BESS

Table 4.9: Results for Before and After Intentional Islanding Equipped with BESS for Case Study 6

Island 1	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info: 1–32, 113–115, 117	$^*G_{10}$	550	450	271.466
	G_{12}	185	85	85
	G_{25}	320	220	220
	G_{26}	414	314	314
	G_{31}	107	7	7
	Total generated power, P_{gen} (MW)		1076	897.466
	Total load, P_{load} (MW)		867.000	867.000
	Total power loss, P_{loss} (MW)		35.328	30.466
	Total power imbalance, P_{imb} (MW)		173.672	0

Island 2	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info: 33–78 116, 118	G_{46}	119	19	19
	G_{49}	304	204	204
	G_{54}	148	148	148
	G_{59}	255	200	200
	G_{61}	260	200	200
	G_{65}	491	391	391
	G_{66}	492	392	392
	$^*G_{69}$	805.2	662.346	312.108

	Total generated power, P_{gen} (MW)		2216.346	1866.108
	Total load, P_{load} (MW)		1819	1819
	Total power loss, P_{loss} (MW)		73.515	47.111
	Total power imbalance, P_{imb} (MW)		323.831	0

Island 3	Generator & BESS info	Max. limit (MW)	Pre-islanding (MW)	Post-islanding (MW)
Buses info: 79–112	G_{80}	577	550	550
	G_{87}	104	104	104
	*G_{89}	707	700	452.064
	G_{100}	352	350	350
	G_{103}	140	140	140
	G_{111}	136	130	130
	B_{82}	300	-	300
	B_{84}	300	-	300
	B_{85}	300	-	138
	B_{86}	300	-	0
	B_{88}	300	-	0
	B_{92}	300	-	0
	B_{93}	300	-	0
	B_{94}	300	-	0
	B_{95}	300	-	0
	B_{96}	300	-	0
	B_{97}	300	-	0
	B_{101}	300	-	0
	B_{102}	300	-	0
	Total generated power, P_{gen} (MW)		1974	2464.064
	Total load, P_{load} (MW)		2385	2385
	Total power loss, P_{loss} (MW)		86.551	79.080
	Total power imbalance, P_{imb} (MW)		-497.551	0

Slack bus

In Island 1, there was a power surplus of 173.672 MW before intentional controlled islanding. A new slack bus, G_{10}, was chosen for Island 1 based on its highest power capacity because the original slack bus was in Island 2. After islanding, load flow analysis was done to balance the system. The result showed that generator G_{10} reduced its power generation from 450 MW to 271.466 MW to balance the island, eliminating the need for the Battery Energy Storage System (BESS) and allowing Island 1 to operate independently as a balanced island.

In Island 2, there was a power surplus of 323.831MW before intentional controlled islanding. The slack bus was in this island, at G_{69}. After islanding, load flow analysis was done to balance the system. The result showed that generator G_{69}

reduced its power generation from 662.346 MW to 312.108 MW to balance the island, eliminating the need for the Battery Energy Storage System (BESS) and allowing Island 2 to operate independently.

In Island 3, a power deficit of 497.551MW occurred because there was no slack bus, which was originally in Island 1. A new slack bus, G_{89}, was chosen for Island 3 based on its highest power capacity. However, the combined maximum power capacity of all generators, totaling 2016 MW, was not enough to meet the load demand of 2385 MW, resulting power deficit of 369W. Therefore, BESS at buses 82, 84, and 85 was needed to provide extra power. The required power support from the BESS needs to be doubled, resulting in up to 738MW to account for the line loss that will occur and leave the slack bus that balances the system. Finally, this allowed Island 3 to meet the power balance criteria, as shown in the Table 4.7. From the total power generated by the BESS, the duration that the BESS can support the system is 4.87 hours. Figure 4.15 present the one-line diagram for Case Study 6 after the integration of a Battery Energy Storage System (BESS), highlighting the location of the BESS necessary in the IEEE 118-bus system to achieve power balance during intentional controlled islanding.

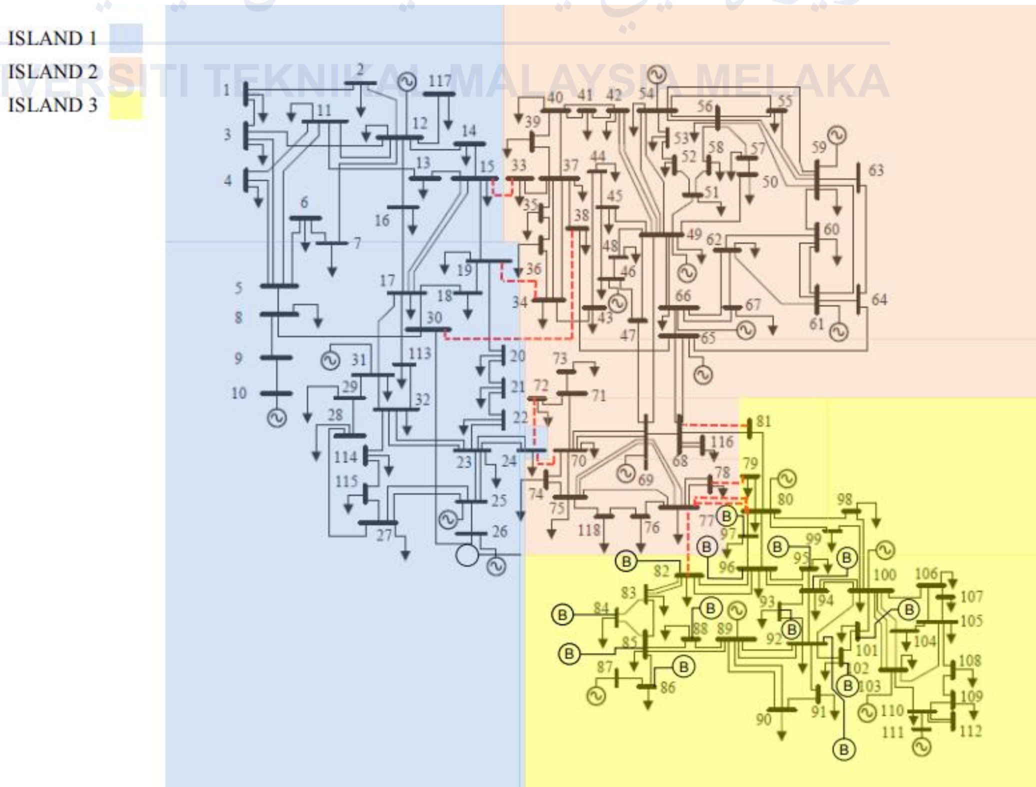

Figure 4.15: One-Line Diagram for Case Study 6 After Integrating BESS

4.6 Chapter Summary

The integration of Battery Energy Storage Systems (BESS) in intentional controlled islanding, as demonstrated in the IEEE 30-bus, 39-bus, and 118-bus systems, proves to be an effective strategy for maintaining power balance during intentional islanding implementation. The strategic placement of BESS units, determined through meticulous line loss analysis, ensures efficient and reliable power distribution, minimizing energy losses and supporting load demands. These case studies prove the viability of BESS in enhancing the resilience and performance of power systems during controlled islanding scenarios.

The results from the case studies underscore the important role of Battery Energy Storage Systems (BESS) in achieving power balance during intentional islanding implementation. BESS units located based on detailed line loss analyses, significantly reduced power imbalances, ensuring reliable and efficient operation of the islands. In the IEEE 30-bus test system, BESS units effectively balanced the islands, demonstrating the feasibility of using BESS for intentional controlled islanding. The integration of BESS at specified buses reduced power losses and ensured the islands met their load demands post-islanding. The IEEE 39-bus and IEEE 118-bus test systems further validated the effectiveness of BESS units in managing larger and more complex power networks. The larger capacity and strategic placement of multiple BESS units were crucial in addressing higher load demands and ensuring minimal power loss across the systems.

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CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study demonstrates that integrating Battery Energy Storage Systems (BESS) is an effective solution for managing power imbalances during intentional controlled islanding implementation. The success of BESS in achieving power balance relies on accurate sizing and strategic placement, with the methodology of using 80% of the total load as the basis for BESS sizing proving effective across all test systems. Additionally, selecting BESS locations based on line loss analysis not only enhances the efficiency of power distribution but also ensures that the islands operate with minimal energy losses. In alignment with our objectives, the study achieved the following: First, it analyzed the size and location of BESS for the IEEE power system network for intentional controlled islanding implementation, confirming that sizing the BESS to 80% of the total load and placing it at locations with the lowest line losses was effective across various test systems. Second, it integrated the BESS into an intentional controlled islanding algorithm, demonstrating a clear methodology for achieving power balance in intentional islands and contributing to reliable and efficient power system operation. Lastly, it evaluates the effectiveness of utilizing BESS in performing intentional controlled islanding by forming balanced islands using IEEE 30-bus, 39-bus, and 118-bus systems, validating that BESS can effectively address deficit power conditions.

5.2 Future Work & Recommendation

Future research could explore dynamic BESS management strategies that consider real-time load changes and the integration of renewable energy sources.

Implementing advanced optimization algorithms, such as those based on machine learning, could further enhance BESS deployment strategies, improving power system efficiency and reliability. Additionally, extending this research to include different types of energy storage systems and their combined use with BESS could provide deeper insights into optimizing energy storage for intentional controlled islanding. It is also recommended to investigate the long-term impacts of BESS deployment on power system stability and economic viability, ensuring the proposed solutions are both technically and financially sustainable

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APPENDIX A

Table A-1: Generator and Load data of IEEE 30-bus systems

Bus	Type Bus	Load (MW)	GEN (MW)
1	Slack	0	414.348
2	PV	21.7	40
3	Load	2.4	0
4	Load	7.6	0
5	PV	94.2	0
6	Load	0	0
7	Load	22.8	0
8	PV	30	0
9	Load	0	0
10	Load	90	0
11	PV	0	0
12	Load	11.2	0
13	PV	0	0
14	Load	6.2	0
15	Load	8.2	0
16	Load	3.5	0
17	Load	9	0
18	Load	3.2	0
19	Load	9.5	0
20	Load	2.2	0
21	Load	17.5	0
22	Load	0	0
23	Load	3.2	0
24	Load	8.7	0
25	Load	0	0
26	Load	3.5	0
27	Load	0	0
28	Load	0	0
29	Load	40	0
30	Load	10.6	0

Table A-2: Generator and Load data of IEEE 39-bus systems

Bus	Type Bus	Load (MW)	GEN (MW)
1	Load	97.6	0
2	Load	0	0
3	Load	322	0
4	Load	600	0
5	Load	0	0
6	Load	0	0
7	Load	233.8	0
8	Load	522	0
9	Load	6.5	0
10	Load	0	0
11	Load	0	0
12	Load	8.53	0
13	Load	0	0
14	Load	0	0
15	Load	320	0
16	Load	329	0
17	Load	0	0
18	Load	158	0
19	Load	0	0
20	Load	680	0
21	Load	274	0
22	Load	0	0
23	Load	700	0
24	Load	308.6	0
25	Load	224	0
26	Load	139	0
27	Load	281	0
28	Load	206	0
29	Load	283.5	0
30	PV	0	650
31	Slack	9.2	632.837
32	PV	0	720
33	PV	0	632
34	PV	0	508
35	PV	0	650
36	PV	0	580
37	PV	0	560
38	PV	0	860
39	PV	1104	1060

Table A-3: Generator and Load data of IEEE 118-bus systems

Bus	Type Bus	Load (MW)	GEN (MW)
1	Load	51	0
2	Load	20	0
3	Load	39	0
4	Load	39	0
5	Load	0	0
6	Load	52	0
7	Load	9	0
8	Load	0	0
9	Load	0	0
10	PV	0	450
11	Load	70	0
12	PV	47	85
13	Load	34	0
14	Load	14	0
15	Load	90	0
16	Load	25	0
17	Load	11	0
18	Load	60	0
19	Load	45	0
20	Load	18	0
21	Load	14	0
22	Load	10	0
23	Load	7	0
24	Load	13	0
25	PV	0	220
26	PV	0	314
27	Load	0	0
28	Load	17	0
29	Load	24	0
30	Load	0	0
31	PV	43	7
32	Load	59	0
33	Load	23	0
34	Load	59	0
35	Load	33	0
36	Load	31	0
37	Load	0	0
38	Load	0	0
39	Load	27	0

Bus	Type Bus	Load (MW)	GEN (MW)
40	Load	66	0
41	Load	37	0
42	Load	0	0
43	Load	18	0
44	Load	16	0
45	Load	53	0
46	PV	28	19
47	Load	34	0
48	Load	20	0
49	PV	0	204
50	Load	17	0
51	Load	17	0
52	Load	18	0
53	Load	23	0
54	PV	113	148
55	Load	63	0
56	Load	84	0
57	Load	12	0
58	Load	12	0
59	PV	277	200
60	Load	78	0
61	PV	0	200
62	Load	77	0
63	Load	0	0
64	Load	0	0
65	PV	0	391
66	PV	0	392
67	Load	28	0
68	Load	0	0
69	Slack	0	662.346
70	Load	66	0
71	Load	0	0
72	Load	12	0
73	Load	6	0
74	Load	68	0
75	Load	47	0
76	Load	68	0
77	Load	0	0
78	Load	71	0
79	Load	39	0
80	PV	130	550

Bus	Type Bus	Load (MW)	GEN (MW)
81	Load	0	0
82	Load	254	0
83	Load	20	0
84	Load	11	0
85	Load	24	0
86	Load	221	0
87	PV	0	104
88	Load	170	0
89	PV	0	700
90	Load	163	0
91	Load	10	0
92	Load	165	0
93	Load	12	0
94	Load	240	0
95	Load	42	0
96	Load	38	0
97	Load	215	0
98	Load	34	0
99	Load	42	0
100	PV	90	350
101	Load	100	0
102	Load	5	0
103	PV	23	140
104	Load	96	0
105	Load	31	0
106	Load	43	0
107	Load	50	0
108	Load	2	0
109	Load	8	0
110	Load	39	0
111	PV	0	130
112	Load	68	0
113	PV	6	0
114	Load	8	0
115	Load	22	0
116	Load	184	0
117	Load	20	0
118	Load	33	0

Table A-4: Total Line Losses Each Bus after adding BESS for IEEE 30-Bus System

Bus	Total loses (MW)	Bus	Total loses (MW)
3	40.82	19	37.096
4	37.215	20	36.694
6	34.828	21	34.603
7	35.067	22	34.718
9	34.421	23	38.159
10	34.425	24	35.661
12	39.254	25	36.041
14	41.454	26	47.594
15	37.849	27	33.232
16	38.401	28	33.818
17	36.152	29	28.87
18	37.981	30	32.949

Table A-5: Total Line Losses Each Bus after adding BESS for IEEE 39-Bus System

Bus	Total loses (MW)	Bus	Total loses (MW)
1	43.058	16	43.243
2	44.258	17	43.348
3	42.427	18	42.733
4	42.959	19	48.896
5	45.082	20	48.807
6	46.018	21	44.212
7	44.318	22	46.104
8	43.623	23	45.350
9	43.320	24	43.172
10	47.942	25	54.533
11	47.279	26	49.413
12	47.731	27	45.589
13	46.908	28	54.324
14	44.360	29	56.852
15	42.740		

Table A-6: Total Line Losses Each Bus after adding BESS for IEEE 118-Bus System

Bus	Total loses (MW)	Bus	Total loses (MW)	Bus	Total loses (MW)
1	208.852	39	197.135	81	183.822
2	208.894	40	195.053	82	137.817
3	207.201	41	199.905	83	142.378
4	206.071	42	203.556	84	158.248
5	205.758	43	207.14	85	147.482
6	205.952	44	210.716	86	153.888
7	205.565	45	205.561	88	154.272
8	204.242	47	204.222	90	160.591
9	210.015	48	208.266	91	165.391
11	202.965	50	210.39	92	152.654
13	208.403	51	206.688	93	153.03
14	208.9	52	212.095	94	141.529
15	195.529	53	209.188	95	144.981
16	208.218	55	196.682	96	143.994
17	199.004	56	195.633	97	154.051
18	198.409	57	211.296	98	177.187
19	195.761	58	208.421	99	169.182
20	207.193	60	196.182	101	157.067
21	213.062	62	196.88	102	156.751
22	215.207	63	194.444	104	160.803
23	207.869	64	194.618	105	160.856
24	203.79	67	203.992	106	162.967
27	211.365	68	189.42	107	174.206
28	214.283	70	189.332	108	177.374
29	211.333	71	195.343	109	181.801
30	198.215	72	212.157	110	188.896
32	205.93	73	202.857	112	199.15
33	203.059	74	184.162	113	204.542
34	192.327	75	179.765	114	211.28
35	194.261	76	180.44	115	211.667
36	194.2	77	172.216	116	189.361
37	192.38	78	173.593	117	223.733
38	192.047	79	176.527	118	180.778