

Multi-purpose Applications of Energy Storage Systems in a Power System Network



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PhD Thesis

*Presented for the degree of **Doctor of Philosophy***

In the Department of Electrical Engineering

University of Cape Town

February 17, 2025

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ACKNOWLEDMENTS

The supervision of the research for this thesis was undertaken by Prof Komla Folly. I appreciate your efforts, patience, insightful feedback, and deep motivation.

Special heartfelt appreciation goes to my wife, Mrs. Stella Okafor, and all my children. Thank you for your love, prayers, and encouragement throughout my study.

To every member of the power research group, University of Cape Town, I say thank you, especially Prof David Oyedokun. Your constructive criticisms, thought-provoking questions, and advice have contributed to no small measure to accomplishing this research.

I appreciate my good friends and colleagues, Azeez Olasoji, Skunana Nkululeko, Mkhutazi Mditshwa, Raymond Ikeleji, and my roommate Isaiah Owoeye. I also appreciate my postgraduate coordinator, Nicole Moodley, for all her assistance to me in the course of my doctoral program.

Additionally, I appreciate the funders of this research project, the Tertiary Education Trust (TETFUND), Abuja Nigeria, the University of Cape Town, postgraduate funding office, and Ekiti State University, Ado-Ekiti, Nigeria, for their financial support.

ABSTRACT

Battery energy storage systems (BESSs) are acknowledged by many researchers as the principal technology required to achieve a high penetration of renewable energy into the electricity network. However, the utilization of a BESS for a single application can lead to under-utilization and may not be economical. This thesis focuses on the multi-purpose applications of a BESS in an electricity grid.

A novel methodology for the optimal sizing of a BESS for the multiple functions of providing support for the frequency nadir (during contingency events), reduction of real power losses, and mitigation of voltage deviations using the deep sleep optimizer (DSO) algorithm was developed. The proposed method establishes a relationship between frequency nadir, voltage variations, power losses, and the BESS multiplier by utilizing regression analysis techniques in multi-objective mathematical formulations. This approach simplifies and enhances the optimization of the multi-objective functions without relying on weighting factors, which are commonly used in many multi-objective optimizations. Additionally, to ensure that BESS capacity meets the acceptable frequency limits during a contingency event in a grid with a high renewable energy penetration, the suggested approach incorporates the rate of change of frequency (RoCoF) for varying degrees of renewable energy penetration. This is extremely important because as the use of renewable energy resources grows, RoCoF values will increase, causing the frequency to fluctuate rapidly during significant grid emergencies. Consequently, in a grid network with a high renewable energy penetration, a suitable RoCoF selection is necessary for sizing the BESS to satisfy the frequency regulation requirements.

When comparing the proposed optimal sizing approach with existing methods, the suggested methodology performed better due to its ability to eliminate the weighting factors, thereby ensuring that none of the objective functions dominate the other. This resulted in a fair optimization process with enhanced results. Additionally, by deploying the new metaheuristic algorithm, the DSO, the computational time was reduced compared with other metaheuristic algorithms such as the particle swarm optimization (PSO) and genetic algorithm (GA).

The optimal placement of a BESS in a power grid network was achieved using a novel placement algorithm that leveraged active power injections from mixed sources of power generation during a power system contingency, along with their corresponding inertia contributions.

To control a BESS for the desired multiple functions, four sub-units of the control system were designed through the use of suitable controllers. These controllers

ensured adequate frequency support during contingency, regulated the charging and discharging actions of the battery, and guaranteed the supply of active and reactive power.

Simulation results showed that through the proposed methodologies, the BESS was able to: (a) sustain the frequency nadir within acceptable limits during an outage of the single largest generating unit; (b) reduce real power losses by about 50%; and (c) improve the voltage profile for all buses in an electricity grid network with a high renewable energy penetration.

TABLE OF CONTENTS

Contents

1. INTRODUCTION	1
1.1 Single-based applications of a BESS.....	3
1.2 Combined applications of a BESS.....	4
1.3 Previous studies	5
1.4 Identification of knowledge gaps.....	133
1.5 Hypothesis.....	133
1.6 Research questions.....	144
1.7 Aims and objectives of the research	144
1.8 Methodology	144
1.9 The key contributions of this study.....	155
1.10 Thesis outline	17
1.11 Summary	19
2. DETERMINATION OF THE OPTIMAL LOCATION FOR A BESS WITHIN A GRID.....	20
2.1 Determination of the optimal location for a BESS in a grid for frequency nadir support during a contingency event.	20
2.2 Determining the optimal location of a BESS to reduce real power losses and mitigate voltage deviations.....	37
2.3 The most critical parameters influencing BESS placement	44
2.4 Summary	44
3. OPTIMAL SIZING OF A BESS FOR MULTIPLE FUNCTIONS	46
3.1 Frequency characteristics of a power system	46
3.2 Proposed methodology for sizing a BESS for multiple functions.....	47
3.3 Test system for establishing the sizing methodology	50
3.4 The fundamentals of regression analysis.....	57
3.5 Determination of the initial capacity of the BESS and its position in the grid.....	60
3.6 Simulations	61
3.7 Summary	80

4. CONTROL OF A BESS FOR MULTIPLE APPLICATIONS	81
4.1 Description of the multi-purpose control strategy for BESS.....	81
4.2 Implementation of the proposed BESS control.	93
4.3 Test Networks	94
4.4 Simulations, results, and discussions.....	95
4.5 Summary	112
5. USING A BESS TO PROVIDE FREQUENCY NADIR SUPPORT DURING CONTINGENCY EVENTS UNDER DIFFERENT GRID CONDITIONS.....	113
5.1 The impact of BESS capacity on the provision of frequency nadir support during a contingency event.	113
5.2 The impact of line lengths on frequency nadir support provided by the BESS during a contingency event.....	115
5.3 Provision of frequency nadir support during a contingency event with varying levels of grid inertia..	116
5.4 The impact of variable output generation from wind plants on frequency nadir support provided by a BESS during a contingency event.	118
5.5 The impact of the size of a power mismatch on the frequency nadir support provided by a BESS during a contingency event.....	122
5.6 Summary.....	122
6. CONCLUSIONS	125
6.1 Response to the research questions.....	126
6.2 Validation of the proposed hypothesis	126
6.3 Recommendations for future work	127
7. REFERENCES.....	128
8. AUTHOR’S PUBLICATIONS FROM THE THESIS.....	141
9. APPENDICES	143
9.1 The PSO codes	143
9.2 The DSO codes (in MATLAB).....	146
9.3 The regression analysis codes (in MATLAB)	149
9.4 Implementation of the BESS control system using DIgSILENT Power Factory (Screenshots).....	151

LIST OF FIGURES

FIGURE 1.1: CLASSIFICATION OF ESSS	1
FIGURE 2.1: STEP-BY-STEP PROCESS FOR DETERMINING THE OPTIMAL LOCATION OF A BESS	26
FIGURE 2.2: THE WESTERN CAPE NETWORK	27
FIGURE 2.3: THE CONVERGENCE OF THE OPTIMIZATION USING PSO.....	32
FIGURE 2.4: THE CONVERGENCE OF THE OPTIMIZATION USING GA.	33
FIGURE 2.5: THE CONVERGENCE OF THE OPTIMIZATION USING FMINCON.	34
FIGURE 2.6: THE FREQUENCY NADIRS OBTAINED AT VARIOUS BESS LOCATIONS .	36
FIGURE 2.7: MINIMUM RoCoF VALUES OBTAINED FROM EACH SOLVER (WITH THE BESS INSTALLED AT BUS 51)	38
FIGURE 2.8: A FLOWCHART SHOWING THE STAGES OF THE OPTIMIZATION.....	40
FIGURE 2.9: ONE-LINE REPRESENTATION OF THE TEST SYSTEM	41
FIGURE 2.10: GRAPHIC REPRESENTATION OF THE OPTIMIZATION CONVERGENCE USING PSO (100 ITERATIONS)	43
FIGURE 2.11: GRAPHIC REPRESENTATION OF THE CONVERGENCE (USING PSO,1000 ITERATIONS).....	44
FIGURE 2.12: VOLTAGE PROFILE IMPROVEMENT THROUGH THE OPTIMAL PLACEMENT OF THE BESS	44
FIGURE 3.1: THE FOUR STAGES OF NOMINAL FREQUENCY RESTORATION	47
FIGURE 3.2: FLOWCHART OF THE BESS SIZING METHODOLOGY.....	49
FIGURE 3.3: TEST SYSTEM FOR ESTABLISHING THE SIZING METHODOLOGY	53
FIGURE 3.4: FREQUENCY RESPONSE PLOTS FOR DIFFERENT LEVELS OF RENEWABLE ENERGY PENETRATION.....	53
FIGURE 3.5: THE RELATIONSHIP BETWEEN FNADIR AND THE BESS MULTIPLIER...	65
FIGURE 3.6: THE RELATIONSHIP BETWEEN PLOSSES AND THE BESS MULTIPLIER .	66
FIGURE 3.7: THE RELATIONSHIP BETWEEN V _D AND BESS MULTIPLIER.....	66
FIGURE 3.8: THE RELATIONSHIP BETWEEN PLOSSES AND FNADIR DETERMINED USING DSO).....	70
FIGURE 3.9: THE RELATIONSHIP BETWEEN PLOSSES AND V _D DETERMINED USING DSO	71
FIGURE 3.10: THE RELATIONSHIP BETWEEN V _D AND PLOSSES DETERMINED USING DSO	71
FIGURE 3.11: THE RELATIONSHIPS AMONG FNADIR, PLOSSES, AND V _D DETERMINED USING GA.....	74
FIGURE 3.12: THE RELATIONSHIP BETWEEN FNADIR AND PLOSSES DETERMINED USING GA	75

FIGURE 3.13: THE RELATIONSHIP BETWEEN FNADIR AND VD DETERMINED USING GA.....	75
FIGURE 3.14: THE RELATIONSHIP BETWEEN VD AND PLOSSES DETERMINED USING GA.....	76
FIGURE 3.15: FREQUENCY RESPONSES USING AN OPTIMALLY SIZED BESS	77
FIGURE 3.16 : GRAPHICAL CORRELATION OF THE VOLTAGE PROFILES OF AFFECTED BUSES (WITH AND WITHOUT BESS).....	80
FIGURE 4.1: BLOCK REPRESENTATION OF THE BESS CONTROL SYSTEM	82
FIGURE 4.2 (A): BATTERY MODEL BLOCK DIAGRAM	84
FIGURE 4.2 (B): BATTERY CELL EQUIVALENT CIRCUIT.....	84
FIGURE 4.3: A BLOCK DIAGRAM OF THE FREQUENCY CONTROL UNIT	88
FIGURE 4.4: THE PQ CONTROLLER MODEL	89
FIGURE 4.5: CHARGE AND DISCHARGE CONTROL.....	91
FIGURE 4.6: FIXED CURRENT AND FIXED VOLTAGE METHOD OF BESS CHARGING	94
FIGURE 4.7: ONE-LINE REPRESENTATION OF THE TEST SYSTEM	95
FIGURE 4.8: FREQUENCY RESPONSE IN THE 12 -BUS TEST NETWORK.	96
FIGURE 4.9: THE REAL POWER INJECTION FROM THE MACHINE AT BUS 2.	97
FIGURE 4.10: THE REAL POWER INJECTION FROM MACHINE AT BUS 3	98
FIGURE 4.11: THE ACTIVE POWER INJECTION FROM THE BESS DURING THE LOAD INCREASE CONTINGENCY.	98
FIGURE 4.12: FREQUENCY RESPONSE IN THE WESTERN CAPE MODIFIED 53-BUS NETWORK.....	99
FIGURE 4.13: REAL POWER INJECTION FOR G1 (WESTERN CAPE MODIFIED 53-BUS TEST SYSTEM)	100
FIGURE 4.14: REAL POWER INJECTION FOR THE GRID (WESTERN CAPE MODIFIED 53-BUS TEST SYSTEM)	101
FIGURE 4.15: REAL POWER INJECTION DIAGRAM FOR THE BESS (WESTERN CAPE MODIFIED 53-BUS TEST SYSTEM).....	101
FIGURE 4.16: FREQUENCY BEHAVIOR DURING A 250 MW DROP IN LOAD (MODIFIED 12-BUS NETWORK)	102
FIGURE 4.17: THE REAL POWER DRAWN BY G2 DURING THE LOAD DECREASE CONTINGENCY (MODIFIED 12-BUS NETWORK)	103
FIGURE 4.18: THE REAL POWER DRAWN BY G3 DURING THE LOAD DECREASE CONTINGENCY (MODIFIED 12-BUS NETWORK)	103
FIGURE 4.19: THE REAL POWER DRAWN BY THE BESS DURING THE LOAD DECREASE CONTINGENCY (MODIFIED 12-BUS NETWORK)	104
FIGURE 4.20: FREQUENCY BEHAVIOR DURING A 350 MW DROP IN LOAD (MODIFIED 53-BUS NETWORK).	106
FIGURE 4.21: REAL POWER DRAWN BY G2 DURING THE LOAD DECREASE CONTINGENCY (MODIFIED 53-BUS NETWORK).....	106

FIGURE 4.22: THE REAL POWER DRAWN BY THE GRID DURING THE LOAD DECREASE CONTINGENCY (MODIFIED 53-BUS NETWORK)	107
FIGURE 4.23: THE REAL POWER DRAWN BY THE BESS DURING THE LOAD DECREASE CONTINGENCY (MODIFIED 53-BUS NETWORK).....	107
FIGURE 4.24: THE SUPPLY OF REACTIVE POWER FROM THE BESS USING THE SUGGESTED TECHNIQUE	109
FIGURE 4.25: IMPROVEMENT IN THE VOLTAGE PROFILE DUE TO THE REACTIVE POWER SUPPLIED BY THE BESS.....	109
FIGURE 4.26: DEACTIVATION OF REACTIVE POWER FUNCTIONALITY IN THE CONTROL SYSTEM (I.E., NO REACTIVE POWER SUPPLIED).....	110
FIGURE 4.27: REAL POWER LOSSES IN THE GRID AT DIFFERENT BESS POSITIONS (MODIFIED 12-BUS NETWORK).	111
FIGURE 5.1: THE FREQUENCY CHARACTERISTICS WITH DIFFERENT BESS CAPACITIES.....	114
FIGURE 5.2: THE ASSOCIATION BETWEEN DIFFERENT BESS CAPACITIES AND FREQUENCY NADIRS.	114
FIGURE 5.3 (A): THE FREQUENCY RESPONSE CHARACTERISTICS (NETWORK WITHOUT A BESS)	117
FIGURE 5.3 (B): DIAGRAM SHOWING THE FREQUENCY RESPONSE CHARACTERISTICS (NETWORK WITH A BESS)	117
FIGURE 5.4 : THE FREQUENCY RESPONSE CHARACTERISTICS UNDER A VARIABLE OUTPUT FROM WPP1	119
FIGURE 5.5: THE REAL INJECTION BY G2 AT THE ONSET OF A CONTINGENCY EVENT	120
FIGURE 5.6: THE REAL INJECTION BY G3 AT THE ONSET OF A CONTINGENCY EVENT	120
FIGURE 5.7: THE ACTIVE POWER INJECTION BY THE BESS AT THE ONSET OF A CONTINGENCY EVENT.....	121
FIGURE 5.8: DIAGRAM SHOWING NO ACTIVE POWER INJECTION BY WPP 1 AT THE ONSET OF A CONTINGENCY EVENT.	121
FIGURE 5.9: DIAGRAM SHOWING NO ACTIVE POWER INJECTION BY WPP 2 AAT THE ONSET OF A CONTINGENCY EVENT.	122
FIGURE 5.10: VARIATION OF THE FREQUENCY NADIR AS THE POWER IMBALANCE INCREASES	123

LIST OF TABLES

TABLE 1.1: SUMMARY OF OPTIMIZATION TECHNIQUES FOR BESS SIZING AND LOCATION.....	7
TABLE 1.2: A COMPARATIVE TABLE SUMMARIZING SELECTED METAHEURISTIC OPTIMIZATION TECHNIQUES.....	10
TABLE 2.1: GENERATION UNITS WITHIN THE WESTERN CAPE NETWORK.....	28
TABLE 2.2: THE PSO METRICS FOR EVALUATING THE OPTIMAL LOCATION FOR A BESS FOR FREQUENCY NADIR SUPPORT	29
TABLE 2.3: THE GA METRICS FOR EVALUATING THE OPTIMAL LOCATION FOR A BESS TO PROVIDE FREQUENCY NADIR SUPPORT.....	29
TABLE 2.4: FMINCON PARAMETERS	30
TABLE 2.5: MINIMUM VALUES OF THE FREQUENCY PARAMETERS	30
TABLE 2.6: THE MINIMUM FREQUENCY NADIR AT DIFFERENT LOCATIONS	35
TABLE 2.7: COMPARISON OF THE RoCoF VALUES USING DIFFERENT ALGORITHMS	37
TABLE 2.8: COMPARISON OF THE BEST (MINIMUM) RoCoF VALUES AND COMPUTATIONAL TIMES FOR THE DIFFERENT ALGORITHMS.....	37
TABLE 2.9: GENERATOR DETAILS	41
TABLE 2.10: SIMULATION RESULTS FOR TOTAL SYSTEM COSTS	42
TABLE 2.11: POWER LOSSES UNDER DIFFERENT NETWORK CONDITIONS.....	44
TABLE 3.1: SUMMARY OF THE GENERATION UNITS IN THE MODIFIED IEEE 39-BUS NETWORK.....	52
TABLE 3.2: PROPORTION OF WIND POWER GRID PENETRATION AND FREQUENCY PARAMETERS.....	53
TABLE 3.3: COMPARISON BETWEEN THE DSO AND HYBRID OPTIMIZATION METHODS (HEURISTIC AND DETERMINISTIC)	54
TABLE 3.4: THE DSO METRICS	57
TABLE 3.5: THE GA METRICS FOR THE OPTIMAL SIZING OF A BESS	57
TABLE 3.6: SIMULATION DATA FOR THE REGRESSION ANALYSIS.....	61
TABLE 3.7: SIMULATION DATA FOR REGRESSION FORMULATION IN PER-UNIT VALUES	62
TABLE 3.8: VALIDATION OF THE APPROPRIATE MODEL FOR EACH DATA SET (R^2 VALUES).....	63
TABLE 3.9: POSSIBLE SOLUTIONS USING DSO.....	67
TABLE 3.10: BEST POSSIBLE SOLUTIONS (BASED ON PRIORITY) USING DSO.....	69
TABLE 3.11: POSSIBLE SOLUTIONS FROM GA.....	72
TABLE 3.12: BEST POSSIBLE SOLUTIONS (BASED ON PRIORITY) USING GA.....	73
TABLE 3.13: MINIMUM FREQUENCIES DURING A CONTINGENCY EVENT.....	77

TABLE 3.14: SUMMARY OF THE BUS VOLTAGES IN NETWORKS WITH AND WITHOUT A BESS).....	78
TABLE 4.1: METRICS OF THE BATTERY MODEL.	87
TABLE 4.2: METRICS OF THE FREQUENCY CONTROLLER	89
TABLE 4.3: METRICS OF THE PQ CONTROLLER.....	91
TABLE 4.4: METRICS OF THE CHARGE/DISCHARGE MODEL.	92
TABLE 4.5: SUMMARY OF THE TEST NETWORK GENERATION CAPACITIES (12-BUS)	94
TABLE 4.6: MAGNITUDES OF THE FREQUENCY NADIRS (12-BUS TEST NETWORK).....	96
TABLE 4.7: REAL POWER INJECTIONS (12-BUS TEST NETWORK)	97
TABLE 4.8: MAGNITUDES OF THE FREQUENCY NADIRS (WESTERN CAPE MODIFIED 53-BUS NETWORK)	99
TABLE 4.9: REAL POWER INJECTIONS (WESTERN CAPE MODIFIED 53-BUS NETWORK)	100
TABLE 4.10: FREQUENCY LEVELS WITH RESPECT TO NETWORK CONDITIONS (MODIFIED 12-BUS NETWORK).....	104
TABLE 4.11: POWER TAKEN FROM THE NETWORK WHEN THE POWER PRODUCED WAS GREATER THAN THE LOAD (MODIFIED 12-BUS NETWORK)	104
TABLE 4.12: FREQUENCY LEVELS WITH RESPECT TO NETWORK CONDITIONS (MODIFIED 53-BUS NETWORK).....	105
TABLE 4.13: POWER TAKEN FROM THE NETWORK WHEN THE POWER PRODUCED WAS GREATER THAN THE LOAD (MODIFIED 53-BUS NETWORK).	105
TABLE 4.14: POWER LOSSES WITH RESPECT TO BESS LOCATIONS. (MODIFIED 12-BUS NETWORK)	111
TABLE 5.1: DIFFERENT BESS CAPACITIES AND FREQUENCY CHARACTERISTICS OF THE TEST SYSTEM.....	113
TABLE 5.2: EFFECT OF TRANSMISSION LINE LENGTH ON FREQUENCY RESPONSE CHARACTERISTICS	115
TABLE 5.3: SUMMARY OF THE FREQUENCY RESPONSE CHARACTERISTICS.	116
TABLE 5.4: FREQUENCY CHARACTERISTICS UNDER A VARIABLE OUTPUT FROM WPP1	118
TABLE 5.5: SUMMARY OF THE NETWORK RESPONSES DUE TO AN INCREASE IN THE POWER IMBALANCE	123

1. INTRODUCTION

For many years, the entire energy sector has depended on the use of carbon-based fuels for the production of electricity, but recently, more sustainable and affordable alternatives have emerged in the form of renewable energy sources. With the Paris Agreement commitments realized, countries and policymakers worldwide have encouraged more participation of renewable energy in their overall generation mix [1]-[3]. The increased penetration of renewable energy resources in the generation portfolio increases the need for adaptability in the generation, transmission, distribution, and utilization of electricity [4]. Energy storage systems (ESSs) could offer this adaptability when optimally integrated into power system networks [5]. There are five major classifications of EESs: chemical, thermal, electrochemical, mechanical, and electrical, as shown in Figure 1.1 [6]-[7].

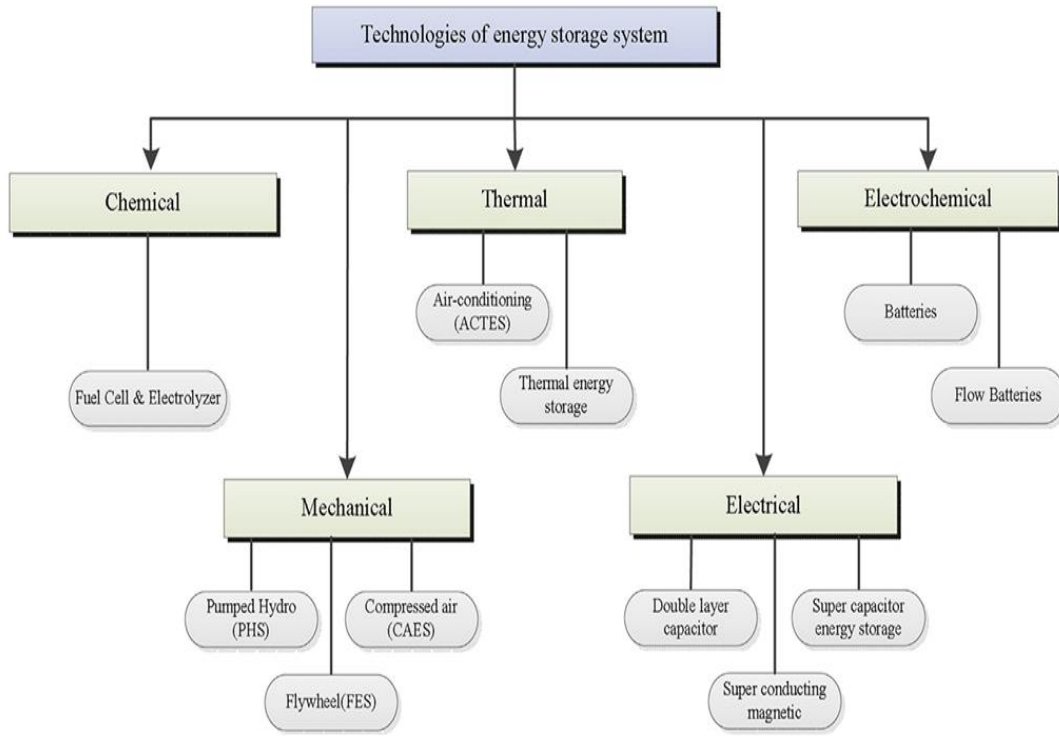


Figure 1.1: Classification of ESSs [6]

The different qualities of the various ESS categories make them appropriate for particular uses in power systems. Among their special characteristics are life cycle, energy density, and power and energy capacity, discharge, and charge time [8].

Electrochemical ESSs, often referred to as chemical-to-electrical EESs, are dependent on the chemical energy present in their active matter for the production of electricity [9]. According to the authors in [10] and [11], chemical-to-electrical EESs include batteries, flow batteries, and hydrogen systems [12]. Based on the technology used, batteries can be further classified as lead-acid, sodium-sulfur, nickel-cadmium, metal-air, zinc-bromine, and lithium-ion batteries, among others [13]- [14].

Battery energy storage systems (BESSs) are capable of providing the robust versatility required to deliver constant, high-quality electricity when appropriately connected to the grid. The pronounced characteristics of battery technologies that account for their flexibility are listed below.

- Ease of installation in power system networks.
- Ability to store electrical energy during excess generation (especially due to weather variability) and deliver it promptly to the grid when the need arises.
- Ability to make power available at the exact place it is needed. This could be at the generation, transmission, or distribution level.
- Battery storage technology can meet the variability of energy consumption.
- Their charging and discharging characteristics could enable them to render several services to the grid.

Battery energy storage systems with lithium-ion technology have several outstanding features that make them highly suitable for power system applications compared to other uses of battery technologies. Some of these unique characteristics are listed below [5], [9], and [15].

- Lithium-ion batteries have a strong energy retention capacity, making them particularly suitable for electric vehicles.
- They have a low self-discharge rate.
- The energy conversion efficiency of a lithium-ion battery is 90–95%. With this high charge/discharge efficiency, there are minimal energy losses during operations.
- Lithium-ion-based battery technology has a long cyclability.
- The charging time for lithium-ion batteries is short in comparison to other battery technologies. This makes them suitable for both electric vehicles and grid applications where a slow recharge process is highly undesirable.
- The power-to-weight ratio of lithium-ion batteries is very high. This feature makes them an ideal battery technology for high-power injection-based applications in grid systems.

- They have low maintenance costs when compared to other technologies such as lead-acid batteries.

In addition to the technical characteristics of lithium-ion batteries listed above, it is important to note that their costs have substantially reduced over time. The project costs for lithium-ion technology are about 50% of the project costs for sodium-sulfur and sodium metal-halide battery technologies [16]. Thus, with its technical and economic advantages, it is envisaged that lithium-ion technology will be the key battery technology used to achieve a high renewable energy penetration in the modern grid. Lithium-ion battery technology was deployed in the work conducted in this study.

1.1 Single-based applications of a BESS

Battery energy storage systems could be deployed into the various voltage levels in grid networks for the following single-based applications [17]:

- Load following: The load following application of BESS ensures that a balance is established between generation and load demand [18]. Through this service, power is made available for a time frame ranging from several minutes to about 10 h [5].
- Consumption flattening: This is a strategy deployed to decrease electrical power consumption when the power utility is experiencing its highest demand. Storage devices are used to conserve inexpensive energy at times of low demand and reintroduce it into electrical networks at periods of high demand, and generation prices are high.
- Time-shifting: Energy from renewable sources in a BESS is time-shifted to correspond with the load pattern [18]. Energy must be provided via storage devices for this service within 5–12 h [18].
- Mitigation of transmission congestion: Battery energy storage systems can store excess generation and make it available when the need arises. Thus, they can be used for mitigating transmission congestion, which arises when the power flows cannot be supported by the transmission infrastructure.
- Fluctuation suppression: This service ensures the smoothing of very short-term (milliseconds) variations in the outputs of renewable-based generating systems. This could be achieved using a BESS.
- Supply of inertia response: The electrical power system relies on the system's instantaneous power reserves, specifically the synchronized generating systems' inertia [19].

- Frequency excursion suppression: Variation in frequency ranging from 1 min to 10 h is known as frequency excursion [20]. A BESS could be deployed to supply the required real power.
- Voltage stability: The researchers in [3] emphasized that the voltage stability of a power grid could be achieved by using BESSs.

1.2 Combined applications of a BESS

In addition to the above specific applications of storage systems in power systems, various combined applications exist. These combined applications are also called multi-purpose or value-stacking applications, and they involve the combination of several individual applications [21]. It involves the use of a storage unit as a multi-functional device that can provide several services to the grid [22]. Applications are combined depending on how compatible they are with one another and the capability of the storage system to meet the requirements of the combined applications [18]. Instances of multiple services that could be provided by BESS include the following.

- Frequency excursion suppression + grid angular stability+ grid voltage stability.
- Power quality+ load shifting + spinning reserve.
- Avoidance of transmission congestion + frequency excursion suppression+ voltage stability.

The authors in [3] reported that an ESS could be used for combined applications in the generation, transmission, and distribution levels of the grid. The following multi-functional applications were proposed.

- Generation level (traditional power plants): energy arbitrage + load following + frequency regulation.
- Generation level (renewable generation): capacity firming + renewable time shift
- Transmission level (high voltage): voltage support + power quality + power reliability.
- Transmission level (medium voltage): peak shaving + power reliability.
- Distribution level: mitigation of voltage deviations + reduction of real power losses + the following load.

1.3 Previous studies

Several studies have been undertaken to investigate the use of BESSs for grid-based utilization. Alhejaj and Gonzalez-Longatt [23] demonstrated that a BESS could be used for the supply of inertia to a grid. In their study, a BESS was integrated into a transmission network, and the outcome of the simulations revealed significant enhancement in frequency during a frequency disturbance event. Similarly, the researchers in [24] and [25] reported that a BESS could be utilized to dampen frequency oscillations arising from the variability of power production from weather-dependent sources of energy.

In addition to the applications of BESS for frequency support, many researchers have also explored the possibility of providing inertia support (using a BESS) for low-inertia power networks. Alhejaj et al. [26] investigated the capability of a grid-scale BESS, providing a frequency response. The authors emphasized that the principal benefits accruing from the application of BESSs for the supply of inertia support include the replacement of fast-start reserve gas turbines, provision of supplementary primary frequency control, and release of additional inertia due to the decline in system inertia. Okafor and Folly [27] discussed the use of a BESS for the provision of inertia in detail. The authors investigated the provision of inertia by a BESS under different grid conditions. The study noted that the length of transmission lines, size of power system disturbance, BESS capacity, and variability of grid inertia significantly impacted the proportion of inertia support derived from a BESS.

Du et al. [28] and Hao et al. [29] conducted a detailed analysis of the effectiveness of a BESS in enhancing short-term voltage stability. They showed that dynamic voltage support could be provided by a BESS to a network during and after a major voltage disturbance event. Static voltage stability improvement was the focus of Tachibana et al. [30] and Adewuyi et al [31]. These studies revealed that a BESS is capable of supplying adequate reactive power to a grid network to boost the system's static voltage stability.

Peak shaving is another area where BESS application has been explored. The researchers in [32] controlled a BESS to provide a peak-shaving service. They developed a methodology that utilized a set point based on the state of charge (SOC) and an algorithm representing the electricity price to create a signal that activated the charge and discharge functions of the BESS. In [33] the authors suggested a control algorithm for BESS to implement peak shaving. Their approach incorporated deep learning and load forecasting. Yong [34] developed a peak shaving algorithm for a microgrid that utilized solar forecasting. Other BESS applications in power system networks that have been explored and

reported in the literature include the reduction of real power losses, mitigation of voltage deviations, and the mitigation and enhancement of the distribution network load and generation hosting capability, respectively [35]–[37].

In addition to these single applications, BESSs can be controlled to provide multiple services. Okafor and Folly [38] used a BESS for the stacking of applications to reduce the underutilization commonly associated with single-based applications. Few previous studies have been conducted in the area of the multi-purpose utilization of BESSs. The principal constraint in the use of BESSs for many applications hinges on the development of an efficient control strategy to enable the implementation of the desired functions [38]. Previous studies have focused on multiple applications of a BESS for the mitigation of voltage and frequency deviations, peak shaving, load levelling and mitigation of voltage rise, power smoothing, and reverse power flow prevention [39]–[41]. Other multifunctional applications include the inertia response and primary frequency reserve, uninterruptible steady supply, and voltage and frequency support [42]–[44]. Additionally, several hybrid BESS control strategies have been reported in the literature. Tang et al. [45] proposed a predictive control for a hybrid EES in electric vehicles, while Chen et al. [46] deployed an improved decentralized control method for a hybrid system consisting of a BESS and a photovoltaic plant. In [47] the authors suggested a reinforcement learning strategy for energy management in a hybrid EES. The proposed technique provided an effective solution to some of the limitations (aging and thermal runaway) associated with the use of BESSs. Zhou et al. [48] developed an integrated control technique for BESSs. Through their suggested approach, the frequency of the power grid was stabilized.

To obtain the maximum benefits of BESS integration to the grid and ensure a rewarding economic payback, the optimal size and location for installing the BESS must be determined. In the literature, several methodologies have been proposed for the optimal capacity and location of a BESS in a grid. Some of these strategies are based on costs, system loadings, RoCoF, and real power losses [49]. Zidar et al. [50] classified all the placement and sizing strategies into four different groups, namely, analytical methods (AM), mathematical programming (MP), exhaustive search (ES), and metaheuristic methods (MH). Analytical methods use statistical data, load demand curves, and mathematical formulas to determine the optimal size and placement for BESS. In MP, the optimal location and size of BESS is determined by developing a mathematical model and providing a solution to it. The major components of MP are the objective function, the constraints, feasible solutions, and the optimal solutions. Mathematical programming can be divided into linear, non-linear, integer, mixed

integer, dynamic, and quadratic programming [50]. The exhaustive search method identifies a search space, evaluates the solutions, compares objective function values, and gives the optimal solution. The major challenge of the ES method is the high degree of computation required. In the metaheuristic method, the search for the optimal solution is accomplished through an artificial intelligence (AI) strategy that mimics natural human/animal behavior or processes. Some examples of these metaheuristic optimizations include the genetic algorithm (GA) [51], artificial bee colony (ABC) [52], teaching, learning based optimization (TLBO) [53], grey wolf optimizer (GWO) [54], and particle swarm optimization (PSO) [55]. Recent advances in AI have resulted in many new metaheuristic algorithms, such as the deep sleep optimizer (DSO) [56], mantis search algorithm (MSA) [57], spider wasp optimization (SWO) [58], and nutcracker optimization algorithm (NOA) [59]. Others in this category include the fig tree-wasp symbiotic coevolutionary algorithm, artificial protozoa optimizer (APO), jellyfish algorithm (JFA), improved pathfinder algorithm (IPFA), and hiking optimization (HO) [60]–[64]. Table 1.1 is a summary of some of the optimization techniques used to determine the optimal size and position of BESSs as found in the literature, while Table 1.2 is a comparative table summarizing selected metaheuristic techniques.

Table 1.1: Summary of optimization techniques for BESS sizing and location.

Reference	BESS applications	Algorithms used for BESS sizing/location	Type of optimization method
[25]	Sizing and siting of the BESS for damping frequency oscillations	The BESS size was estimated using network parameters such as inertia constant, and system size, allowable RoCoF and magnitude of power imbalance. while the Prony method was used to determine the optimal location for BESS	Analytical method
[36]	Optimal sizing and siting of BESS for mitigation of the voltage deviation, reduction of peak	The optimal BESS size was determined using a mathematical relationship between BESS maximum energy, minimum energy, and	The analytical method was deployed for sizing while the location was determined

	demand, and real power losses	minimum depth of discharge while the siting of BESS was achieved based on the bus with the least value for the formulated cost function.	using metaheuristic optimization methods: PSO and GA
[42]	Determination of the size of the hybrid BESS for supply of inertia and primary frequency reserve.	The techniques for the sizing of BESS were two-folds. The storage size for the inertia response was estimated using a region reduction method, while the BESS size for primary frequency regulation was achieved analytically.	Analytical method and metaheuristic: TLBO
[62]	Optimal sizing of BESS for frequency stability	Determination of the optimal size was based on the magnitude of the network load.	Analytical method
[65]	Determination of the capacity of BESS for the inertia response and primary frequency reserve	The sizing method deploys mathematical formulations based on the network parameters [inertia constant, system power (MVA), and rate of change of frequency (RoCoF)].	Analytical method.
[66]	Optimal sizing and placement of BESS for the reduction of the root-mean-square error of voltage	The BESS size evaluated using a power sensitivity matrix and the optimal location was based on the bus with the highest value of the formulated objective function	Analytical method

[67]	Assessment of the ideal size and position of the BESS to enhance investment efficiency, minimize power losses, and mitigate power fluctuations.	The minimization of the BESS investment costs was the criteria used in determining the optimal location for the BESS.	Metaheuristic: Memetic salp swarm algorithm
[68]	Optimal sizing and placement of the BESS for the improvement of system frequency stability	The optimization strategy seeks the best improvement in the nadir and RoCoF, while the BESS size and location served as the optimization constraints	Three Metaheuristic methods: PSO, firefly, and BAT
[69]	Optimal location and sizing of the BESS to improve frequency response	Optimal placement of the BESS was based on a sensitivity analysis targeting minimum line loadings, while the optimal sizing was accomplished by minimizing the frequency duration and RoCoF following a load tripping event	Analytical method for the optimal location and deployment of ABC and PSO
[70]	Optimal sizing of the BESS for the regulation of voltage and management of peak load.	The optimal size of the BESS was based on a cost-benefit analysis	Analytical method
[71]* Proposed for this Thesis	Identification of the optimal site for the BESS to ensure sufficient frequency regulation in contingency events.	The best position of the BESS was found based on the real power released from the generating units at the instant of contingency.	Metaheuristic: PSO and GA. Mathematical programming: fmincon.

[72]* Proposed for this Thesis	Determination of the optimal size of BESS for multiple services to the grid	The optimal size of the BESS for the multiple functions was achieved using a regression analysis for the formulation of the objective functions	Metaheuristic: DSO and GA
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**References [71] and [72* are proposed in this thesis; however, the results are already published.*

Table 1.2: A comparative table summarizing selected metaheuristic optimization techniques [51]–[52], [54]–[56]

Feature	PSO	GA	GWO	ABC	DSO
Source of inspiration	Birds flocking	Darwin's theory of evolution by natural selection	Hierarchy in the leadership and hunting strategy of grey wolves	Honeybee foraging (searching) behavior	Human sleep cycle
Tuning parameter	Inertia weight, cognitive coefficient	Population size, mutation rate, and cross over rate	Number of wolves	Number of scout bees	Number of sleep cycles, depth of sleep.
Solution presentation	Particles	Chromosomes which are encoded as binary numbers.	Positions of wolves	Food sources	Each individual becomes a candidate solution
Speed of convergence (execution time)	Fast convergence	Moderately fast convergence	Fast convergence	Moderately fast	Fast convergence
Computational complexities	Minimal computation	Moderately complex, involves more evaluations	Minimal computation	Moderately complex, more evaluations	Minimal computations
Execution time	Low (<1 s)	Medium (1–10 s) to high (>10 s)	Low (< 1 s)	Medium (1–10 s)	Low (<1 s)

Feature	PSO	GA	GWO	ABC	DSO
Key process	Updating velocity and position	Selection, cross-over, mutation	Encircling its prey, hunting and attacking	Employed bees	Uses previous solutions to influence the current search. When it encounters stagnation in the improvement of the solutions, it enters into deep sleep, thus, reducing the computational effort as well as the number of solutions and time taken to reach the optimal solution.
Ability to explore	High especially in the early iterations	May be high depending on the mutation rate	High, balance exploration with exploitation as a result of social hierarchy	High exploration due to the introduction of diversity scout bees	High exploration, balances exploration and exploitation. The sleep mechanism in DSO plays a crucial role in balancing exploration and exploitation, thus, helping it to effectively search

					the solution space.
Ability to exploit	Strong exploitation	Moderate depending on selection	Strong exploitation (converges towards the alpha wolves).	Moderate. It could be improved by adaptive strategies.	Strong balances exploration with exploitation. Through the light sleep/awake phase, the agents move randomly in the search solution space, promoting exploration. In the deep sleep phase, refinement and consolidation of the previous best solution are achieved, thereby promoting exploitation.

Notes: The values above for execution time apply to light weight optimization problems on a modern standard personal computer (for example, those with Intel i5/i7 processors).

In addition to properly sizing and positioning the BESS in the grid, the efficiency of the BESS control strategy plays an important role in the overall effectiveness of the BESS. Importantly, without a good control system, it will be impossible for a BESS to be deployed for multifunctional applications. Lee et al. [39] proposed a coordinated control algorithm to enable the minimization of the impact of frequency and voltage deviations by a BESS. Additionally, Deeba et

al. [40] focused on implementing a reduction in peak load, load levelling, and the mitigation of voltage rise through their multifunctional BESS control system. The challenges of reverse power flow arising from a high penetration of renewable energy resources was addressed by Akagi et al. [41]. In their study, a BESS was able to deliver several services, including power smoothing and the prevention of reverse power flow. The provision of frequency support and a steady supply of power were accomplished via the control system developed by Serban and Marinescu [44]. Kumar et al. [73] developed a control strategy for a BESS to offer the dual services of frequency and voltage support.

1.4 Identification of knowledge gaps

From the literature reviewed on the sizing, placement, and application of BESSs in the power grid, the following knowledge gaps were identified:

- The existing BESS sizing methodologies do not incorporate a specific level of renewable contribution to the energy mix. Therefore, as the grid penetration of renewable energy increases, the RoCoF during contingency events also increases, and the frequency rises/falls more rapidly [27].
- The BESS placement strategies for the support of frequency used in the literature were not based on the global RoCoF system and real power injections from generation sources. However, the frequency nadir during contingency is greatly influenced by the aforementioned parameters.
- The multi-objective optimization methods used for the sizing and placement of BESS depend on the use of weighting factors. This has many negative consequences, as reported by authors in [74] and [75]. These consequences include biased solutions, with some of the Pareto solutions completely missed, and skewed optimization (as a result of mis-scaled weight), leading to the dominance of one objective over the other.
- The BESS deployment in power grids has not focused on rendering multiple services. This leads to the underutilization of a BESS [21], [76].

1.5 Hypothesis

This study established the following hypothesis:

"The multi-purpose applications of a BESS for frequency nadir support during a contingency event, reduction of real power loss, and mitigation of voltage deviation will result in the full utilization of the BESS (with enhanced economic benefits). This will also reduce some of the challenges associated with the intermittent nature and high penetration of renewable generation (wind and solar photovoltaic) in a power system grid network. This will increase both the system frequency stability and voltage stability and ensure the maximum utilization of renewable generation through the appropriate balancing of generation and load."

1.6 Research questions

The following research questions will be answered in this thesis:

- What is the optimal size of the EES selected for use in the power system grid network?
- What is the optimal location of the EES in the power system grid network, and how will it be determined?
- What control methodology will be deployed for the implementation of the multiple functions of frequency nadir support during a contingency event, reduction of power losses, and mitigation of voltage deviations?

1.7 Aims and objectives of the research

This research aimed to integrate a BESS into an electric network with a high renewable energy penetration for the provision of frequency nadir support during a contingency event, reduction of real power losses, and minimization of the impact of voltage deviation. The specific objectives were:

- Determination of the optimal location of the BEES within the grid.
- Determination of the optimal BEES size for the desired multiple functions.
- Development of a control system for multi-purpose BEES applications.

1.8 Methodology

The methodology applied for this work proceeded in three stages. The first stage examined the placement strategy for a BESS within the grid network for the provision of frequency nadir support during contingency events, reduction of real power losses, and mitigation of voltage deviations. Based on active power injections during contingency events, a novel approach for determining the optimal position of a BESS in the grid was developed using inertia constant contributions from varying generation sources and a global RoCoF system. These power system parameters greatly influenced the frequency nadir during contingency events. Comprehensive details of this novel placement methodology for a BESS (with all mathematical formulations and a summary flowchart) are given in Chapter 2 of this thesis.

The second stage of the methodology considered how the optimal size of the storage system should be determined. A novel regression-based sizing technique

(for BESS multi-purpose applications) was established. The novel method determines the relationships between frequency nadir, voltage variations, power losses, and the BESS multiplier using regression analysis techniques in multi-objective mathematical formulations. Unlike many other multi-objective optimizations where weighting factors are commonly used, this method makes optimizing the multi-objective functions simpler and more effective without using weighting factors. Additionally, to ensure that the BESS capacity meets the acceptable frequency limits (during contingency) in an electric power grid with a high renewable energy penetration, the suggested sizing approach incorporates the RoCoF for varying degrees of renewable energy resources. This is extremely important because as the use of renewable energy sources grows, RoCoF values climb upwards, causing the system frequency to fluctuate rapidly during significant power system emergencies. Consequently, in a grid network with a high renewable energy penetration, a suitable RoCoF selection is necessary for BESS sizing to satisfy the frequency regulation requirement. The full details of this new BESS optimal sizing technique are provided in Chapter 3 of this thesis.

The control of the BESS for multiple applications, i.e., frequency support (during contingency events), reactive power supply, reduction of real power losses, and mitigation of voltage deviations, was the primary focus of the third stage of the methodology.

To enable the BESS to implement the tasks described above, three sets of controllers were designed and connected appropriately. The controllers used were frequency controllers, charge controllers, and active/reactive power controllers. The frequency controller determines the magnitude of real power to be delivered at the occurrence of a contingency event. The charge controller housed the charging algorithms, while the PQ controllers controlled both the real and reactive power. An in-depth analysis of this novel control strategy is given in Chapter 4 of this thesis.

1.9 The key contributions of this study.

The key contributions of this research were as follows:

- 1 Using the DSO algorithm, a novel approach for the optimal sizing of a BESS to provide frequency nadir support during contingency events, reduction of real power losses, and mitigation of voltage deviations was developed. The proposed method established a relationship between frequency nadir, voltage variations, power losses, and the BESS multiplier using regression analysis techniques in multi-objective mathematical formulations. Unlike many other multi-objective optimizations where weighting factors are commonly used, this method makes

optimizing the multi-objective functions simpler and more effective without using weighting factors.

Comparing the proposed optimal sizing approach with the existing methods, the novel methodology performed better due to its ability to eliminate the weighting factors, thereby ensuring that none of the objective functions dominated the other. This results in a fair optimization process with better results. Moreover, by deploying the new metaheuristic algorithm, the DSO, the computational time is reduced when compared with other metaheuristic algorithms such as the PSO and GA.

2 To ensure that BESS support for frequency meets the acceptable frequency limits (during a contingency event) in an electricity network with a high proportion of renewable energy resources, the suggested sizing approach incorporated the RoCoF for varying degrees of renewable energy resources. This is extremely important because as the use of renewable energy sources grows, the RoCoF values climb upwards, causing the system frequency to fluctuate rapidly during significant power system emergencies. As a result, in a grid network with a high renewable energy penetration, a suitable RoCoF selection is necessary for determining the BESS size to satisfy the frequency regulation requirement.

3 A novel methodology for identifying the optimal location of a BESS in a power system network based on active power injections (during a power system contingency event), inertia constant contributions (from mixed sources of power generation) and a global RoCoF system was proposed. These power system parameters greatly influenced the frequency nadir during contingency.

4 The research revealed the impacts of transmission line lengths on the frequency support (during contingency) provided by BESS. The results of this work revealed that there is an inverse relationship between transmission line lengths and RoCoF (during contingency). As the transmission line increased in length, the RoCoF value decreased (under the same load and contingency conditions). Therefore, this should be accounted for when determining the size of BESS for frequency support, otherwise, the BESS may be over-sized as a result of the inherent low RoCoF of a long transmission line.

5. The study revealed how the power converter (PC) capacity affects the active power injected by BESS during contingency events. The degree of active power injected at contingency determines whether a BESS can effectively provide frequency nadir support during a contingency event. As the magnitude of the power imbalance increases, BESS responds accordingly by injecting more real power to compensate for the power mismatch, resulting in a positive linear

relationship between the magnitude of power imbalance and injected real power from the BESS. However, immediately after the PC capacity is exceeded, a further increase in the magnitude of the power imbalance will no longer result in a corresponding increase in the amount of real power injected by the BESS. This implies that the active power released by the BESS may no longer be sufficient to provide adequate support for the frequency nadir during contingency because of the restriction on the amount of injected power introduced by the PC capacity. The consequence of this is a rapid decrease in the frequency.

1.10 Thesis outline

Chapter 1 examines the reasons for the increase in the integration of renewable energy resources in power system networks. It discusses the various classifications of EESs, with an emphasis on BESSs. The key outcomes were:

- A presentation of the unique features of lithium-ion battery energy storage technology that make it suitable for grid applications.
- A presentation of the single and multiple-based grid applications of BESSs.
- A literature review covering the strategies for determining the optimal size and location of a BESS in a power system network.
- A tabular comparison of metaheuristic optimization algorithms.

Chapter 2 focuses on the determination of the optimal location for a BESS in the test systems. It discusses the mathematical formulations for the determination of the optimal location of a BESS for the regulation of frequency and the optimal location of a BESS for the reduction of power losses and mitigation of voltage deviations. This chapter clarifies how the minimization of RoCoF could be used to identify the optimal location for BESS placement in a power system grid network. Furthermore, it provides a step-by-step approach to using a cost function (due to active power losses and voltage deviations) to determine the optimal location for BESS placement for the reduction of real power losses and mitigation of voltage deviations. The key outcomes were:

- The optimal location of a BESS for the provision of frequency support during a power mismatch was determined.
- The optimal location of a BESS for the reduction of real power losses and mitigation of voltage deviations was determined.

Chapter 3 discusses the frequency characteristics of a power system network under different levels of penetration by renewable energy resources. It shows the step-by-step approach required for the implementation of the novel regression-based multi-objective optimization (for the sizing of BESS for multiple applications).

The chapter explains the derivation of the mathematical formulations for the regression analysis equations used in the study and displays the simulation data sets.

The chapter concludes with the presentation of the results obtained from the application of DSO and GA in solving the multi-objective functions. It also provides the methodology for the multi-purpose applications of BESS. It reviews the concepts of regression analysis and demonstrates how the technique is applied to formulate the objective functions needed to determine the optimal size of a BESS for multiple functions. The key outcomes were:

A tabular presentation of the magnitudes of the RoCoF and frequency nadirs as the grid penetration of renewable energy increased in the test system.

- Development of regression-based multi-objective functions for frequency nadir support, reduction of real power losses, and mitigation of voltage deviations.
- Determination of the optimal size of BESS for the multiple functions of frequency nadir support, reduction of real power losses, and mitigation of voltage deviations.

Chapter 4 presents an extensive description of the proposed multi-purpose control strategy for a BESS. It describes the four subunits (battery unit, frequency controller model, charge controller model, and active and reactive power controller model) of the control system and shows the mathematical formulations that govern their operations. It provides design calculations for all parameters deployed in the control system.

It also provides insights into how the proposed control system could be implemented in the DIGSILENT Power Factory software.

Finally, it showcases the results obtained from the implementation of the suggested control system. The key outcome was:

- A determination of the parameters used in the battery model and all controllers.

Chapter 5 discusses the application of a BESS for the support of a frequency nadir (during a power mismatch) under different conditions in the grid network. The different network conditions included wind generation variability, different transmission line lengths, different magnitudes of power mismatch, different wind penetrations, different BESS capacities, and different magnitudes of sudden change in loads. The key findings were:

- The existence of a strong positive correlation between the BESS capacity and frequency nadir during a power mismatch. As the capacity of BESS increased, the frequency nadir improved.
- A demonstration of the need for BESS integration for frequency improvement as the grid penetration of renewable energy increases.
- The identification of an increasing linear relationship between active power injection from BESS and the magnitude of the power mismatch. As the power mismatch increased, the active power injection from the BESS also increased. However, this relationship ceased to hold once the converter was exceeded, and the relationship became approximately constant.

Chapter 6 concludes this thesis and addresses the research questions posed in Chapter 1, which are related to the hypothesis, and recommendations for future work.

1.11 Summary

The focus of Chapter 1 was a discussion of the varieties of ESSs and their uses in power grid networks. The unique features of a lithium-ion based BESS that makes it highly suitable for power system applications compared to other battery technologies were examined. A literature review of the applications of BESSs, and the optimal sizing, placement, and control methodologies for a BESS was conducted. Additionally, research questions, hypothesis, methodologies, thesis outlines, and a comparative table of metaheuristic algorithms based on source of inspiration, tuning parameters, solution presentation, speed of convergence, computational complexities, execution time, and ability to explore were presented in Chapter 1.

2. DETERMINATION OF THE OPTIMAL LOCATION FOR A BESS WITHIN A GRID

The effectiveness of a BESS in providing essential services to a grid network depends on its capacity, location in the grid network, and the control strategy deployed for the BESS. Improper placement of a BESS may increase the investment costs and result in technical issues, such as an increase in real power losses and deviations in voltage [77]–[79]. The integration of a BESS in a grid network could be for single or multiple applications, such as in [80]–[83]. The BESS placement strategies developed in this chapter focused on enhancing the frequency nadir (during contingency events) and the reduction of real power losses and mitigation of voltage deviations.

The optimization of mathematical formulations for the enhancement of frequency nadir was based on real power injections from mixed sources of generation, inertia constant contribution, and a global RoCoF system. These parameters greatly influence the magnitude of the frequency nadir (during contingency events). The optimal location for frequency is considered to be the bus within the grid that has the minimum RoCoF.

The second placement methodology addressed the reduction of real power losses and mitigation of voltage deviations. The objective function for the optimization was based on total system costs due to real power losses and voltage deviations. The bus within the test system with the lowest system cost was selected as the optimal location for the reduction of real power losses and the mitigation of voltage deviations.

2.1 Determination of the optimal location for a BESS in a grid for frequency nadir support during a contingency event

In power system stability studies, the fundamental equation that relates the frequency of the system, inertia constant, power system size, and the mismatch between real power generation and load demand is given in equation (2.1), according to [65], [84]–[85]:

$$\frac{2H_{sys}df}{f_0 dt} = \frac{P_g - P_l}{S_{sys}} = \frac{\Delta P}{S_{sys}} \quad (2.1)$$

where S_{sys} is the rating of the power system; H_{sys} is inertia constant; $\frac{df}{dt}$ is the RoCoF; f_0 is the frequency of the system; ΔP is the real power mismatch; P_g is the real power generated (also called mechanical power); and P_l is the load demand (also known as electrical power).

Considering n -numbers of power generating units, the total inertia constant H_{sys} is given in equation (2.2):

$$H_{sys} = \frac{\sum_1^n H_i S_i}{S_{sys}} \quad (2.2)$$

where H_i is the inertia constant for the i th energy source and S_i is the MVA capacity of the i th energy source.

From equation (2.1), making $\frac{df}{dt}$ the subject of the formula results in equation (2.3):

$$\frac{df}{dt} = \left(\frac{\Delta P}{S_{sys}}\right)\left(\frac{f_0}{2H_{sys}}\right) \quad (2.3)$$

Equation (2.2) is substituted into equation (2.3) to obtain equation (2.4):

$$\frac{df}{dt} = \left(\frac{\Delta P}{2\sum_1^n H_i S_i}\right)(f_0) \quad (2.4)$$

2.1.1 Mathematical formulation for determining the optimal location for a BESS for frequency nadir support during a contingency event

Considering a grid network, where there are total of N -machines connected with a sum of M -loads, the power-load balance equation is given in equation (2.5):

$$\sum_{i=1}^N P_{iactg} = \sum_{i=1}^M P_{iactl} + \sum P_{actll} \quad (2.5)$$

where P_{iactg} is the real power production from the synchronous machine located at the i th bus; P_{iactl} , is the load demand from the i th bus, and $\sum P_{actll}$ is the total line losses. Equation (2.5) could be interpreted as: total power generated in the network = total loads connected to the network + total active power losses.

Assuming the grid network consists of synchronous machine units, non-synchronous machine units, and BESSs, then equation (2.5) could be rewritten according to equation (2.6):

$$\sum_{i=1}^N P_{iactg} + \sum_{j=1}^{M_r} P_{jactren} + \sum_{k=1}^{K_{es}} P_{kactes} = \sum_{i=1}^M P_{iactl} + \sum P_{actll} \quad (2.6)$$

where N is the total number of connected synchronous machine units; M_r is the total units of renewable energy sources; and K_{es} is the number of connected energy storage units. The real generations at the i th, j th, and k th buses (from the synchronous machine, renewable energy source, and storage unit) are P_{iactg} , $P_{jactren}$, and P_{kactes} respectively.

Equation (2.4) can be re-written to incorporate all sources of power generation:

$$\frac{df}{dt} = \frac{\Delta P}{2(\sum_{i=1}^N S_{ig}H_{ig} + \sum_{j=1}^{Mr} S_{jren}H_{jren} + \sum_{k=1}^{Kes} S_{kes}H_{kes})} (f_0) \quad (2.7)$$

where the system sizes (in MVA) for the synchronous machine unit, renewable energy unit, and storage unit are S_{ig} , S_{jren} , and S_{kes} respectively; and H_{ig} , H_{jren} , and H_{kes} are the inertia constants provided by the synchronous machine, renewable energy source, and storage unit, respectively.

For a load increase or generator outage event, at the very instant of the contingency event, the synchronous machines will naturally inject real power to address the short fall in real power generation. Assuming that the storage unit and renewable energy sources are equipped with appropriate controllers to support inertia, they will also participate in the injection of real power during the contingency event. The real power gain from the generation sources will be incorporated into equation (2.6) and the power deficit equation will be defined as follows:

$$\Delta P = (\sum_{i=1}^N P_{iactg} + \sum_{i=1}^N \Delta P_{iactg} + \sum_{j=1}^{Mr} P_{iactren} + \sum_{j=1}^{Mr} \Delta P_{iactren} + \sum_{k=1}^{Kes} P_{iactes} + \sum_{k=1}^{Kes} \Delta P_{iactes}) - (\sum_{i=1}^M P_{iactl} + \sum P_{actll}) \quad (2.8)$$

where, $\sum_{i=1}^N \Delta P_{iactg}$, $\sum_{j=1}^{Mr} \Delta P_{iactren}$, and $\sum_{k=1}^{Kes} \Delta P_{iactes}$ are the real power injections from the synchronous machine, renewable energy source, and energy storage unit, respectively.

Equation (2.8) was substituted into equation (2.7) to get :

$$\frac{df}{dt} = \left\{ \frac{(\sum_{i=1}^N P_{iactg} + \sum_{i=1}^N \Delta P_{iactg} + \sum_{j=1}^{Mr} P_{iactren} + \sum_{j=1}^{Mr} \Delta P_{iactren} + \sum_{k=1}^{Kes} P_{iactes} + \sum_{k=1}^{Kes} \Delta P_{iactes}) - (\sum_{i=1}^M P_{iactl} + \sum P_{actll})}{2(\sum_{i=1}^N S_{ig}H_{ig} + \sum_{j=1}^{Mr} S_{jren}H_{jren} + \sum_{k=1}^{Kes} S_{kes}H_{kes})} \right\} (f_0) \quad (2.9)$$

Renewable energy resources are connected into a grid network through a power electronic interface [86] and therefore require special methods to contribute inertia to the grid. These methodologies are extensively discussed in [87]-[90]. Through the methods, inertia is supplied from renewable energy sources; however, this will be at the expense of the full utilization of their capacity (with part of their total power used as a reserve for the provision of inertia).

For this thesis, the maximum utilization of the renewable energy sources was desired; therefore, no part of the output was used for the provision of inertia to the grid.

The best site for the installation of BESS in the network for the provision of support for the frequency nadir is therefore the bus that will give the minimum value for $\frac{df}{dt}$, as given in equation (2.9). Therefore, the objective function for the optimal placement of BESS for frequency support (during a contingency event) is the minimization of $\frac{df}{dt}$.

2.1.2 Optimization constraints

The optimization process for equation (2.9) is subject to the frequency, SOC of the battery, converter capacity, and voltage constraint equations. These are provided in equations (2.10) to (2.12):

$$f_{min} < f < f_{max} \quad (2.10)$$

where f is the frequency during the optimization process and f_{min} and f_{max} are the lowest and highest acceptable frequencies, respectively.

$$20\% \leq SOC \leq 80\% \quad (2.11)$$

Equation (2.11) signifies the SOC constraint for the BESS. The SOC values were set according to equation (2.11) to ensure the health and longevity of the battery. Negative consequences, such as thermal runaway, electrode degradation, cell imbalance, and reduced battery life may arise when the battery is overcharged or discharged below the acceptable minimum level.

The PC capacity influences the magnitude of the real power either released by a BESS at the occurrence of a load increase power mismatch or absorbed from the grid (for charging purposes) during a load decrease power imbalance. Therefore, the PC capacity (S_{concap}) must be greater than the real power injected/used by a BESS in the event of a power mismatch according to equation (2.12):

$$P_{conmax} \leq S_{concap} \quad (2.12)$$

where S_{concap} is the size of the converter and P_{conmax} is the highest power delivered from the converter.

Equation (2.13) gives the constraint imposed upon the voltage. This helps in maintaining an acceptable voltage level on the buses during optimization:

$$V_{min} \leq V_i \leq V_{max} \quad (2.13)$$

where V_i is the voltage at the i th bus; and V_{min} and V_{max} signify the lowest and highest voltage levels, respectively.

2.1.3 Methodology for determining the optimal location for a BESS in a grid

The strategy deployed in this study to determine the optimal location for the installation of a BESS in a grid to provide frequency nadir support during a contingency event was two-fold. First, the network adopted for the study was modeled for a load flow analysis and the implementation of a load increase contingency. Prior to the modeling of the network, the BESS size (100 MW) for frequency support was estimated based on the inertia constant contribution of all the generating units in the test system according to Knap et al. [65]. The second stage was an optimization process, with the objective function given in equation (2.9). The results from the load flow analysis and load increase contingency were used as the input variables for optimizing the objective function formulated in equation (2.8). The optimization was executed in the MATLAB environment using the PSO algorithm, GA, and fmincon MATLAB solver. The step-by-step approach is given below with the corresponding flow chart summarized in Figure 2.1.

- (1) The network data was obtained, and the parameters of the optimization algorithm were established.
- (2) The BESS capacity for frequency support was determined based on the system inertia constant according to Knap et al. [65].
- (3) A candidate bus was chosen for the BESS capacity determined in step 2.
- (4) A load increase contingency event was created using the DIgSILENT Power Factory software.
- (5) The optimization model was established using the objective function given in equation (2.8) with all the system constraints observed.
- (6) The optimization algorithm was executed to evaluate the objective function.
- (7) If not every bus has been chosen as a candidate bus, the procedure returned to step 3.
- (8) If every bus has been chosen as a candidate bus, the bus with the lowest RoCoF is selected as the most suitable for BESS placement for frequency support.

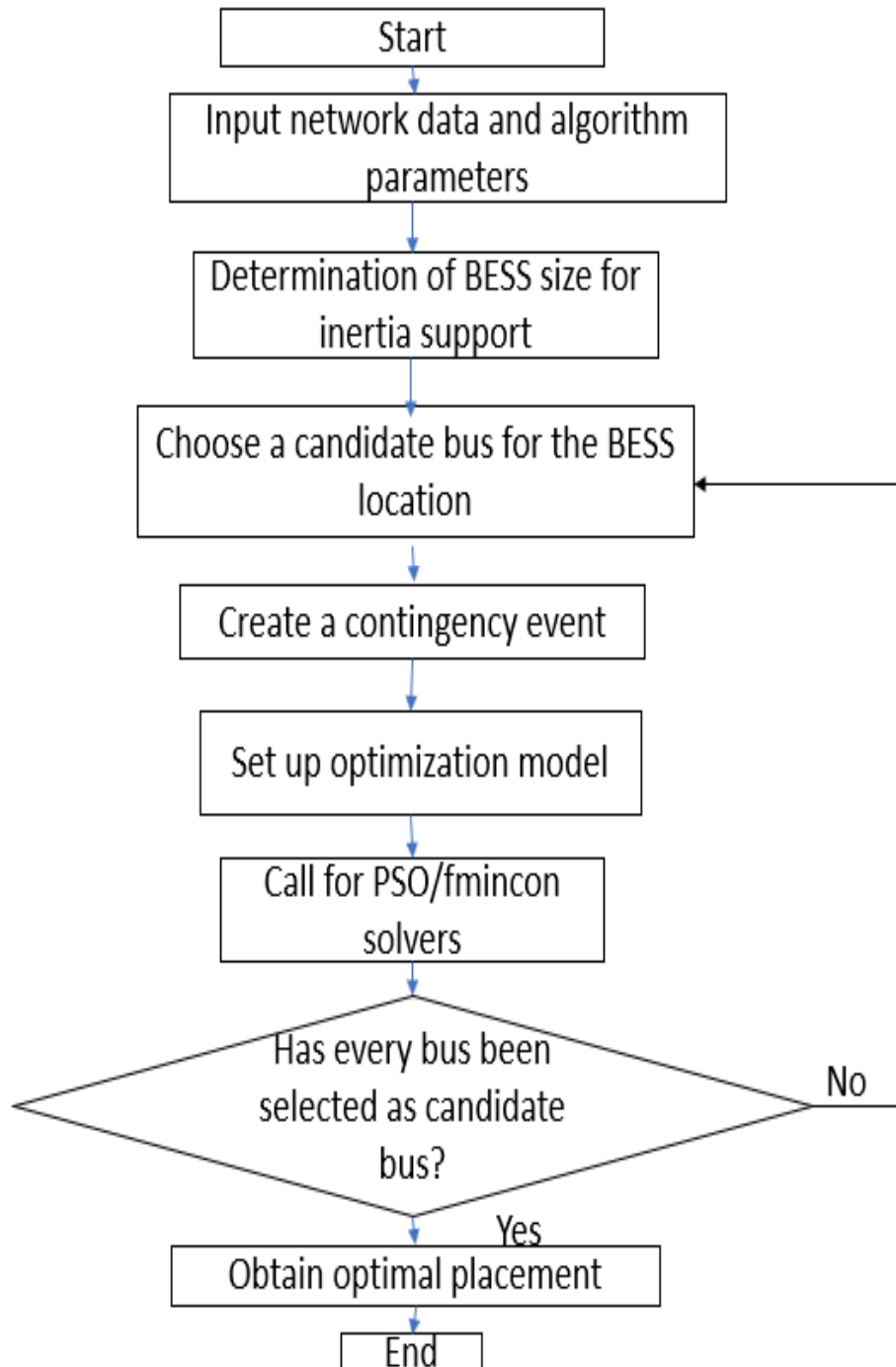


Figure 2.1: Step-by-step process for determining the optimal location of BESS

2.1.4 Test system (Western Cape Network [91])

The test network used in this study was the 53-bus transmission network shown in Figure 2.2. The generation units are summarized in Table 2.1. The frequency is 50 Hz, and the allowable voltage (in pu) at any bus (V_i) was in accordance with equation (2.14). This test system, being a transmission network, was used for the optimal placement of a BESS for frequency regulation.

$$0.95 \leq V_i \leq 1.05 \quad (2.14)$$

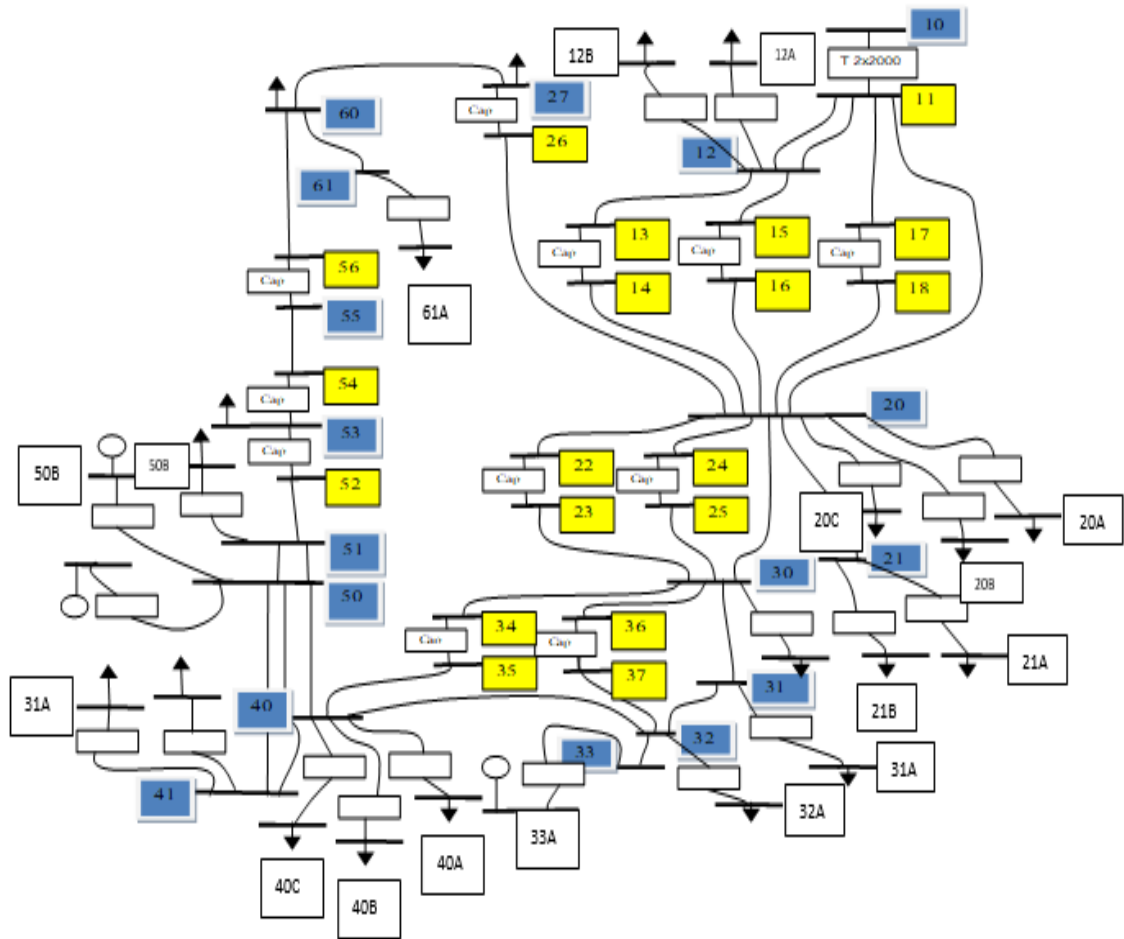


Figure 2.2: The Western Cape Network [91]

Table 2.1: Generation units within the Western Cape Network

Power plant	Power (MVA)	Power (MW)
Ggrid	4000	3400
G1	235	200
WPP1	250	150
WPP2	250	150
WPP3	250	150
WPP4	250	150
BESS	100	100

Where Ggrid and G1 are synchronous generators and WPP1-WPP2 are wind power plants.

2.1.5 Particle swarm optimization (PSO)

The PSO was first used in 1995 in [92]–[94], and was proposed as a population-based metaheuristic optimization technique. It was inspired by the natural flocking habits of birds [95], [96]. In this optimization technique, a swarm consisting of N -particles moves in various routes. Each particle is represented as X_i (where $i = 1, 2, 3, \dots, N$). The motion of the particles occurs in various directions D , expressed as X_{ij} (with j being taken from $1, 2, 3, \dots, D$). Then, $X_{ij} = (X_{i1}, X_{i2}, X_{i3}, \dots, X_{iD})$ for every particle, and the velocity is defined as $V_{ij} = (V_{i1}, V_{i2}, V_{i3}, \dots, V_{iD})$.

An update on the velocity and position of the particles was obtained using equations (2.15) and (2.16):

$$V_{i,j}^{k+1} = w V_{i,j}^k + c_1 r_1 (P_{best\ i,j}^k - X_{i,j}^k) + c_2 r_2 (G_{best\ i,j}^k - X_{i,j}^k) \quad (2.15)$$

$$X_{i,j}^{k+1} = X_{i,j}^k + V_{i,j}^{k+1} \quad (2.16)$$

where $P_{best\ i,j}^k$ and $G_{best\ i,j}^k$ are the best current and search positions; w is the inertia weight, c_1 and c_2 are acceleration factors; and r_1 and r_2 are random numbers generated between 0 and 1. The PSO codes (in MATLAB) deployed in this thesis are provided in Appendix 8.1, while the PSO metrics for the optimal location of a BESS in a grid network for the regulation of frequency during a contingency event are given in Table 2.2. The inertia weight (highest), inertia weight (lowest), and acceleration factors used are benchmarked values from the literature. A population size of 500 was selected to enable a wide search for the optimal solution, while a maximum iteration of 100 was adopted to reduce computational complexities.

Table 2.2: The PSO metrics used for evaluating the optimal location for a BESS to provide frequency nadir support.

Parameter	Values
Population	500
Inertia weight (maximum)	0.90
Inertia weight (minimum)	0.40
Acceleration factor	2.05
Maximum iterations	100

2.1.6 Genetic algorithm (GA)

The GA is a search-based method for optimization. It was inspired by Darwin's theory of evolution by natural selection and works based on the survival of the fittest [97]-[99]. Through heuristically generated solutions, an initial set of solutions (called the population) is produced. The next step involves the evaluation of the fitness value, followed by the selection of the parents. The selection of two parents achieves an enhanced fitness value. A new population is generated by crossover and mutation involving the selected parents and their offspring. This process continues with the newly generated population until the criteria for termination are implemented. The effectiveness of the GA is strongly influenced by the crossover and mutation rates [100]-[103]. The MATLAB GA toolbox was used in this thesis, with the GA metrics presented in Table 2.3. The crossover probability, mutation probability, and acceleration factor were benchmarked from the literature, while population size and maximum iterations were selected in line with the PSO to enable a robust comparison of the results.

Table 2.3: The GA metrics for evaluating the optimal location for a BESS to provide frequency nadir support

Parameters	Values
Population size	500
Crossover probability	0.80
Mutation probability	0.20
Acceleration factor	2.05
Maximum iterations	100

2.1.7 Fmincon MATLAB Solver

Fmincon (i.e., function minimization with constraints) is an optimization solver in the MATLAB toolbox. It provides solutions to an optimization problem with constraints. The metrics of the fmincon solver are given in Table 2.4. The lower

and upper bounds were determined based on the optimization control variable, while the initial guess was randomly chosen but was close to the lower bound.

Table 2.4: Fmincon parameters

Parameter	Value
Initial guess	20.5
Lower bound	24
Upper bound	37.5

2.1.8 Simulations, results, and discussion

2.1.8.1 Simulations, results, and discussions (Western Cape Network)

The optimization objective function developed to determine the optimal location in the test system for the installation of a BESS is given in equation (2.9). This equation was solved by deploying three optimization solvers. The algorithm was selected to compare results from a metaheuristic algorithm (PSO and GA) and a deterministic algorithm (fmincon). The test system deployed was the Western Cape 53-bus network. The results obtained are given in Table 2.5, while Figure 2.3 to Figure 2.5 provide graphic presentations of the results.

Table 2.5: Minimum values of the frequency parameters (Western Cape Network)

Serial number	Bus number where the BESS is connected	RoCoF (Hz/s) using PSO	RoCoF (Hz/s) using fmincon	RoCoF (Hz/s) using GA
1	61	0.4653	0.4661	0.4661
2	35	0.4923	0.4931	0.4932
3	60	0.7256	0.7282	0.7269
4	20B	0.7615	0.7641	0.7628
5	61A	0.7365	0.7391	0.7378
6	56	0.6306	0.6317	0.6317
7	55	0.6746	0.6758	0.6758
8	54	0.7016	0.7027	0.7028
9	53	0.6530	0.6541	0.6541
10	52	0.7530	0.7556	0.7543
11	51	0.8365	0.8394	0.8379
12	51A	0.7395	0.7421	0.7408
13	50	0.7323	0.7348	0.7336
14	50A	0.6736	0.6748	0.6748
15	40	0.7270	0.7296	0.7283

16	40A	0.7296	0.7321	0.7309
17	41	0.6293	0.6303	0.6304
18	41A	0.6852	0.6863	0.6864
19	27	0.6462	0.6484	0.6473
20	26	0.6651	0.6663	0.6663
21	12	0.6335	0.6357	0.6346
22	12A	0.7474	0.7500	0.7487
23	12B	0.6558	0.6569	0.6570
24	11	0.5891	0.5901	0.5901
25	20	0.5463	0.5472	0.5472
26	13	0.6086	0.6097	0.6097
27	14	0.6122	0.6132	0.6133
28	15	0.5656	0.5665	0.5666
29	16	0.5402	0.5411	0.5412
30	17	0.5390	0.5409	0.5399
31	18	0.7212	0.7237	0.7224
32	30	0.6254	0.6272	0.6262
33	22	0.6799	0.6810	0.6811
34	23	0.5272	0.5281	0.5281
35	24	0.6533	0.6555	0.6544
36	25	0.5570	0.5590	0.5580
37	20A	0.5118	0.5126	0.5126
38	20C	0.5501	0.5510	0.5510
39	21	0.6216	0.6226	0.6227
40	21A	0.6147	0.6157	0.6157
41	21B	0.5385	0.5394	0.5395
42	31	0.5496	0.5506	0.5506
43	30A	0.5820	0.5830	0.5831
44	31A	0.5605	0.5614	0.5615
45	32	0.6099	0.6120	0.6109
46	32A	0.5534	0.5543	0.5544
47	33A	0.5852	0.5862	0.5862
48	33	0.5089	0.5098	0.5098
49	34	0.5186	0.5195	0.5195
50	10A	0.4829	0.4837	0.4837
51	36	0.5118	0.5126	0.5127
52	37	0.5342	0.5351	0.5352
53	10	slack bus	slack bus	slack bus

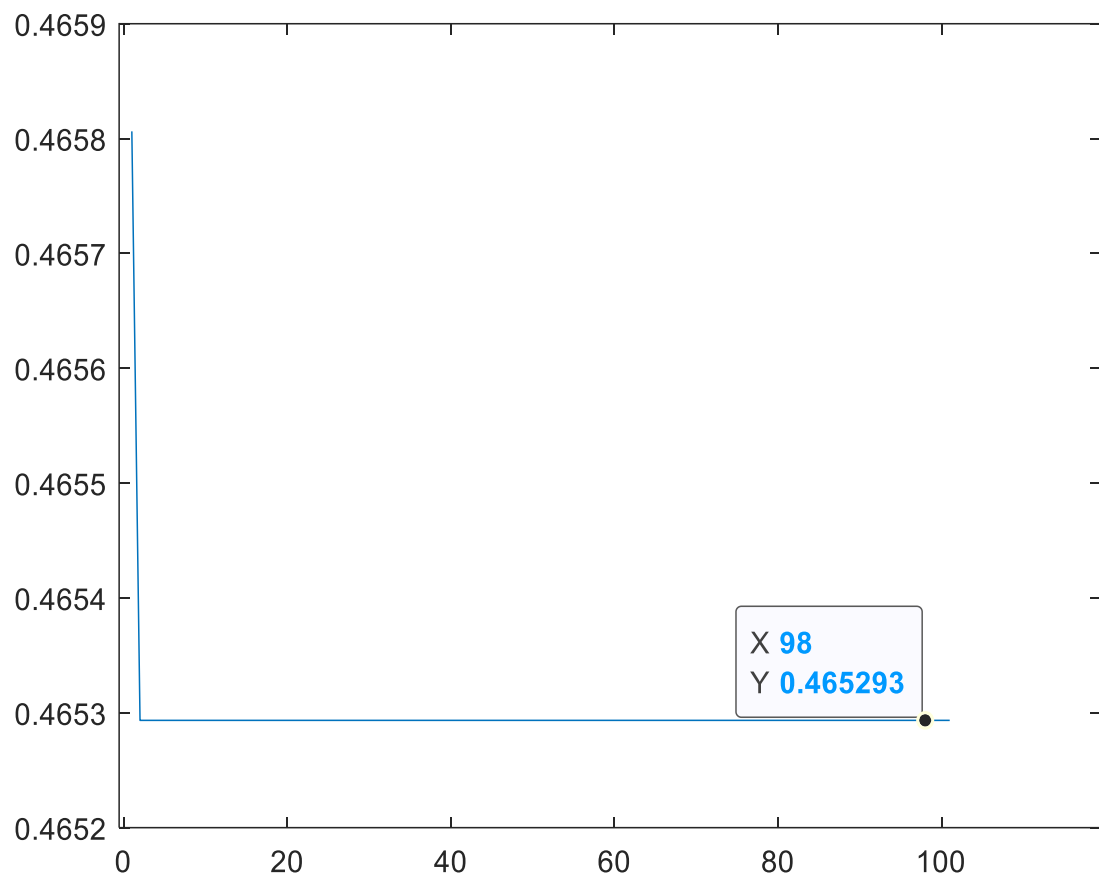


Figure 2.3: The convergence of the optimization using PSO.

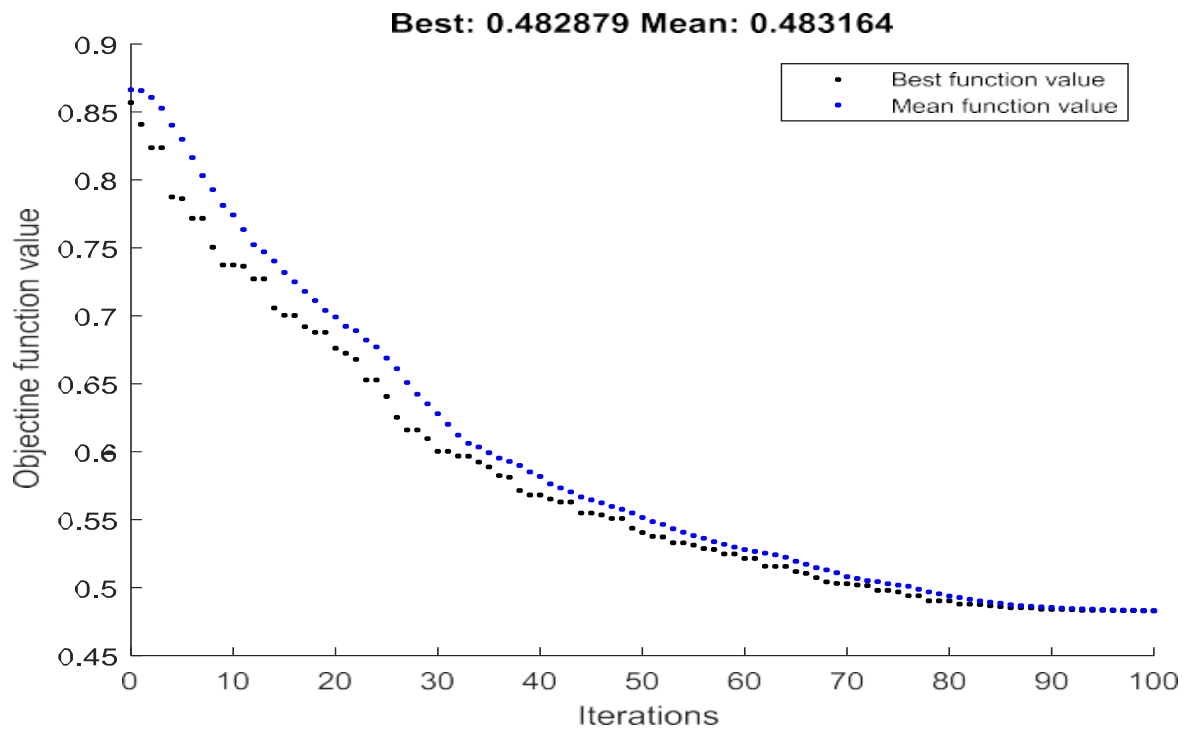


Figure 2.4: The convergence of the optimization using GA.

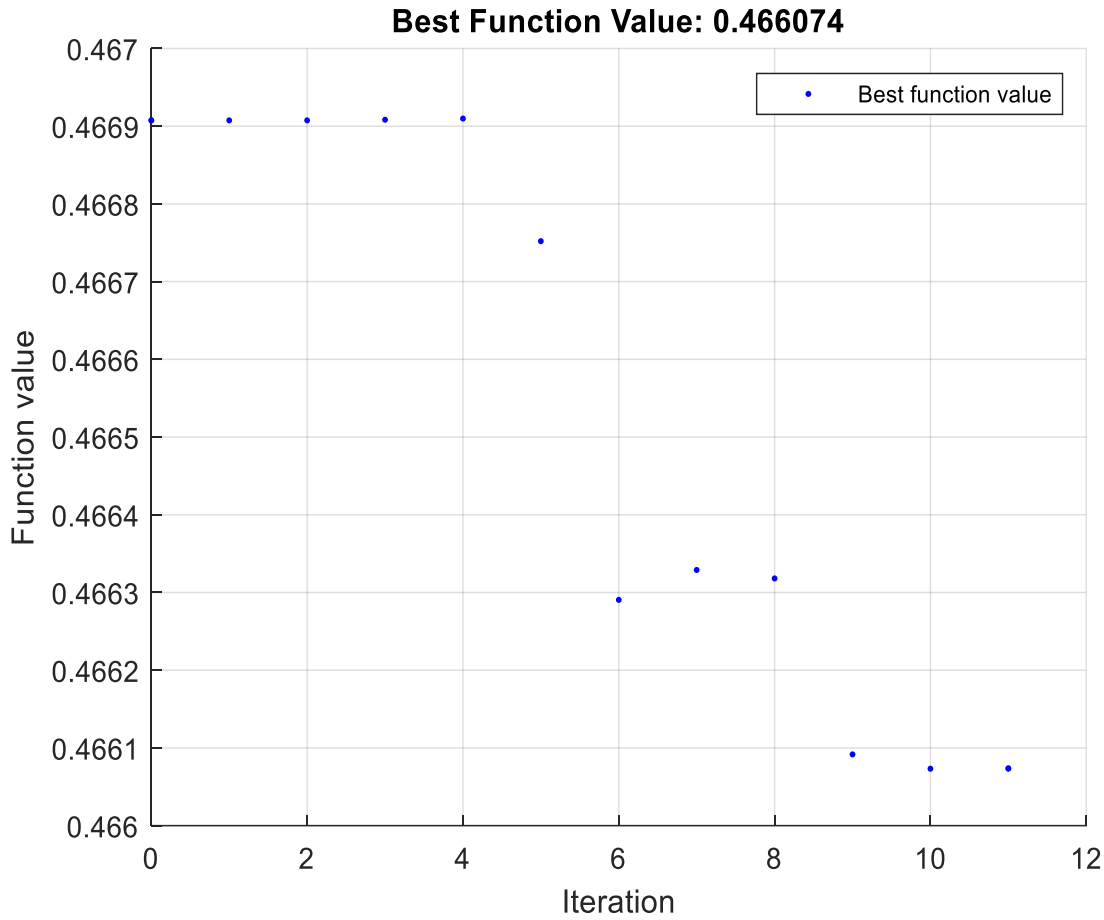


Figure 2.5: The convergence of the optimization using fmincon.

A load increase contingency of 1320MW (at bus 51) was activated at 5 seconds during a 10 seconds simulation. Table 2.5 shows that an increase in load (1320 MW) resulted in varying RoCoF values as the BESS location in the power network changed. Specifically, when using the PSO, the RoCoF was lowest (0.4653 Hz/s) when the BESS was located at bus 61, but was highest (0.8365 Hz/s) when the BESS was placed at the worst bus position bus 51. This means that if the BESS was located at bus 51 and there was a contingency event, the frequency would fall more rapidly than when it was placed at bus 61 for the same degree of contingency. The RoCoF was nearly double at bus 51, highlighting the significant impact of BESS location on frequency stability during contingency events. Installing the BESS at bus 51 is therefore undesirable because it could cause the frequency to drop below the threshold value according to grid guidelines. Hence, in the test system, bus 61 was the optimal location for the integration of the 100 MW BESS to provide frequency nadir support during a contingency event. This placement will produce the minimum magnitude of the

RoCoF and thereby ensure that the frequency does not rapidly decline with the occurrence of a frequency disturbance event.

2.1.8.2 Simulations, results, and discussions (minimum frequency nadirs at different BESS locations)

This scenario investigated how the position of the BESS in a network could affect the nadir during a load increase contingency of 1350 MW. The capacity of the battery was 100 MW, with the load unexpectedly raised by 1350 MW after 5 s. The simulations had a duration of 10 s. The various cases examined were:

- The test system with no BESS
- The test system with a BESS at bus 51 (non-optimal location)
- The test system with a BESS at bus 10A (close to the optimal location)
- The test system with a BESS connected optimally (at bus 61)

Table 2.6 shows the lowest frequency nadir attained during the various scenarios considered. The corresponding graphic representations of the frequency nadirs are shown in Figure 2.6.

The results revealed that the BESS provided the maximum support for sustaining the frequency nadir at 49.60 Hz (during the load increase contingency) when it was connected at its optimal location (i.e., bus 61).

Table 2.6: The minimum frequency nadir at different locations

BESS location	Frequency nadir (Hz)
No BESS	49.43
Non-optimal location (bus 51)	49.49
Near the optimal location (bus 10A)	49.56
Optimal location (bus 61)	49.60

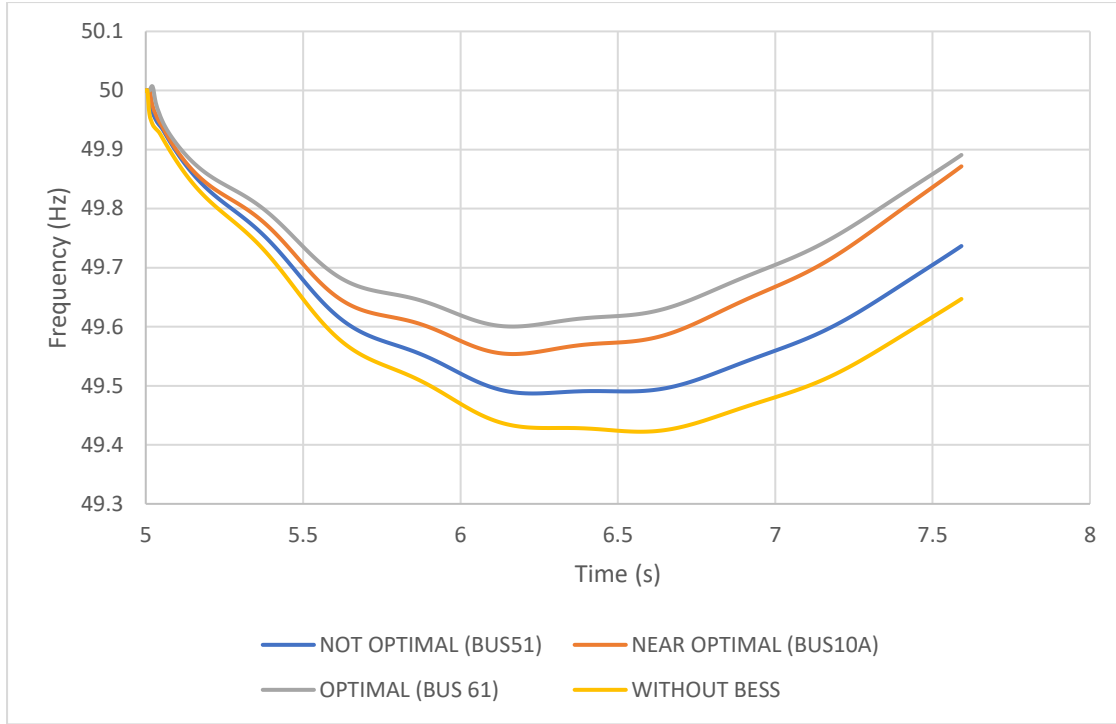


Figure 2.6: The frequency nadirs obtained at various BESS locations

2.1.8 3 Simulations, results, and discussions (comparison of algorithms).

The effectiveness of the algorithms deployed were compared to determine the optimal location for the BESS. The effectiveness was assessed using indices based on the solver's ability to achieve the lowest value for the RoCoF and the shortest computational time. Table 2.7 presents the RoCoF values in order of descending magnitude for the three optimization solvers, while Table 2.8 compares their minimum RoCoF values and computational times.

The PSO consistently outperformed the two other algorithms (GA and fmincon) in finding the lowest value for the RoCoF, which assisted in finding the optimal location to install a BESS in the Western Cape modified 53-bus system. Table 2.8 shows the superiority of PSO over GA and fmincon in searching for the optimal value for RoCoF (0.4653 Hz/s). It is also evident from Table 2.8 that using the PSO resulted in the shortest computational time (0.0206 s). This was because the PSO used basic arithmetic operations, no selection, crossover, or mutation computation, and had faster tuning parameters.

Figure 2.7 shows a comparison of the minimum values of RoCoF obtained using each solver with the BESS integrated into the non-optimal location of bus 51.

Table 2.7: Comparison of the RoCoF values using different algorithms

S/N	BUS NO for BESS	RoCoF (Hz/s) using PSO	RoCoF (Hz/s) using fmincon	RoCoF (Hz/s) using GA	S/N	BUS NO for BESS	RoCoF (Hz/s) using PSO	RoCoF (Hz/s) using fmincon	RoCoF (Hz/s) using GA
1	51	0.83651	0.83941	0.83792	27	21A	0.61467	0.6157	0.61575
2	20B	0.76146	0.76411	0.76279	28	14	0.6122	0.61323	0.61327
3	52	0.75299	0.75561	0.75431	29	32	0.60985	0.61196	0.61091
4	12A	0.74736	0.74996	0.74867	30	13	0.60863	0.60965	0.74078
5	51A	0.73949	0.74205	0.74078	31	11	0.58911	0.59011	0.59014
6	61A	0.73654	0.73909	0.73784	32	33A	0.58519	0.58617	0.58621
7	50	0.73229	0.73483	0.73357	33	30A	0.58203	0.58301	0.58305
8	40A	0.72959	0.73212	0.73087	34	15	0.56561	0.56654	0.56659
9	40	0.72703	0.72955	0.72831	35	31A	0.56051	0.56144	0.56148
10	60	0.72563	0.72815	0.72691	36	25	0.55702	0.55896	0.55801
11	18	0.72117	0.72367	0.72242	37	32A	0.55341	0.55434	0.55438
12	54	0.70156	0.70274	0.70279	38	20C	0.55006	0.55098	0.55102
13	41A	0.68518	0.68633	0.68638	39	31A	0.54964	0.56144	0.56148
14	22	0.67986	0.68111	0.68105	40	20	0.54627	0.54718	0.54722
15	55	0.67464	0.67577	0.67582	41	16	0.54022	0.54113	0.54116
16	50A	0.67361	0.67475	0.67479	42	17	0.53911	0.54087	0.53994
17	26	0.66513	0.66625	0.66629	43	21B	0.53853	0.53943	0.53947
18	12B	0.65582	0.65692	0.65697	44	37	0.53422	0.53512	0.53516
19	24	0.65324	0.65551	0.65438	45	23	0.52718	0.52806	0.52811
20	53	0.65311	0.65409	0.65414	46	34	0.51858	0.51945	0.51949
21	27	0.64618	0.64842	0.64731	47	36	0.51177	0.51263	0.51267
22	12	0.63351	0.63571	0.63462	48	20A	0.51176	0.51262	0.51266
23	56	0.63063	0.63169	0.63173	49	33	0.50894	0.50981	0.50983
24	41	0.62926	0.63032	0.63036	50	35	0.49229	0.49312	0.49316
25	30	0.62535	0.62724	0.62616	51	10A	0.48287	0.48368	0.48371
26	21	0.62158	0.62262	0.62267	52	61	0.46529	0.46607	0.46611

Table 2.8: Comparison of the best (minimum) RoCoF values and computational times for the different algorithms.

Algorithm	Minimum RoCoF (Hz/s)	Computational time (s)
PSO	0.4653	0.0206
GA	0.4661	0.8057
Fmincom	0.4661	0.6550

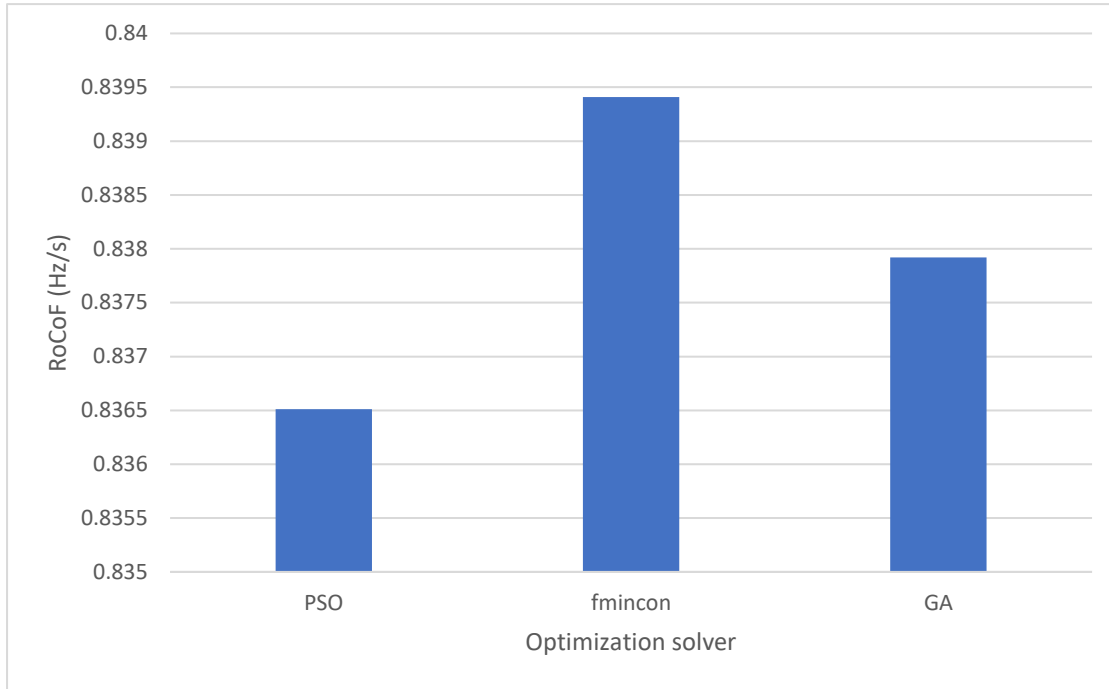


Figure 2.7: Minimum RoCoF values obtained from each solver (with the BESS installed at bus 51)

2.2 Determining the optimal location of a BESS to reduce real power losses and mitigate voltage deviations

Installing a BESS in the optimal location could help reduce real power losses and mitigate voltage deviations in the test system. However, integrating a BESS into the grid network at non-optimal locations could increase the real power losses. It may adversely affect the magnitude of every bus voltage in the test network.

2.2.1 Mathematical formulations for determining the optimal location for reducing real power losses and mitigating voltage deviations

In this thesis, the optimal location for the installation of a BESS was identified as the bus (integrated with a BESS) that minimizes the overall costs associated with real power losses and voltage deviations. This approach integrated the BESS in a way that effectively reduced both the costs due to real power losses and voltage deviations. The mathematical formulations are given in equations (2.17) to (2.20). The cost due to power losses is given in equation (2.19) while the cost due to voltage deviation is given in equation (2.20). The total system costs are defined by equation (2.18). The bus with the minimum total system cost (i.e., the cost

arising from power losses and voltage deviations) was considered to be the optimal position for the integration of a BESS.

$$\text{Objective function} = \text{Min} (C_{sys}) \quad (2.17)$$

$$C_{sys} = C_{PL} + C_{VR} \quad (2.18)$$

$$C_{PL} = \sum_{t=1}^T \sum_{i=1, j \neq i}^m \{ (V_i)^2 + (V_j)^2 - 2(V_i) \times (V_j) \times (\cos(\delta_i - \delta_j)) \} \{ (G_{ij}) \times (\gamma_{loss}) \} \quad (2.19)$$

$$C_{VR} = \sum_{t=1}^T \sum_{i=1}^N (| V_i^2 - V_{ref}^2 |)^{1/2} (\gamma_{VR}) \quad (2.20)$$

where C_{sys} is the total system cost arising from real power losses and voltage deviations, C_{PL} is the cost arising from real power losses only; C_{VR} is the cost as a result of voltage deviation; N is the total number of buses in the network; m is the sum of the branches in the test system; V_i and V_j represent the voltage magnitudes at the i th and j th buses, respectively; G_{ij} is the line conductance between the i th and j th buses; δ_i is the phase angle for the voltage at the i th bus, while that of the j th bus is δ_j . The cost due to real power loss (γ_{loss}) is 0.284 \$/kWh [36], [37], and γ_{VR} is the rate of voltage deviation cost, which is 0.142 \$/p.u [36], [37]. The total time period in hours is T

To minimize equation (2.17) the voltage and the SOC constraints given previously in equations (2.13) and (2.10), respectively, were observed.

2.2.2 Methodology for the assessment of the optimal location to install a BESS for the reduction of real power losses and mitigation of voltage deviations

To determine the optimal location of a BESS, the test network was modeled in a simulation environment. A BESS capacity of 1.55 MW was estimated based on the system loads and active power losses in the network without BESS integration. The BESS was then connected to any bus chosen as a candidate bus, and a load flow was performed for each configuration. The parameters from the load flow studies were used as input data for optimization using the newly developed objective function. The optimization was implemented using PSO and fmincon in the MATLAB environment. The process continued until the objective function was evaluated for BESS connection at all buses, with the exception of the slack bus. The optimal location was considered to be the bus where the system cost was lowest. These optimization stages are summarized in the flowchart in Figure 2.8

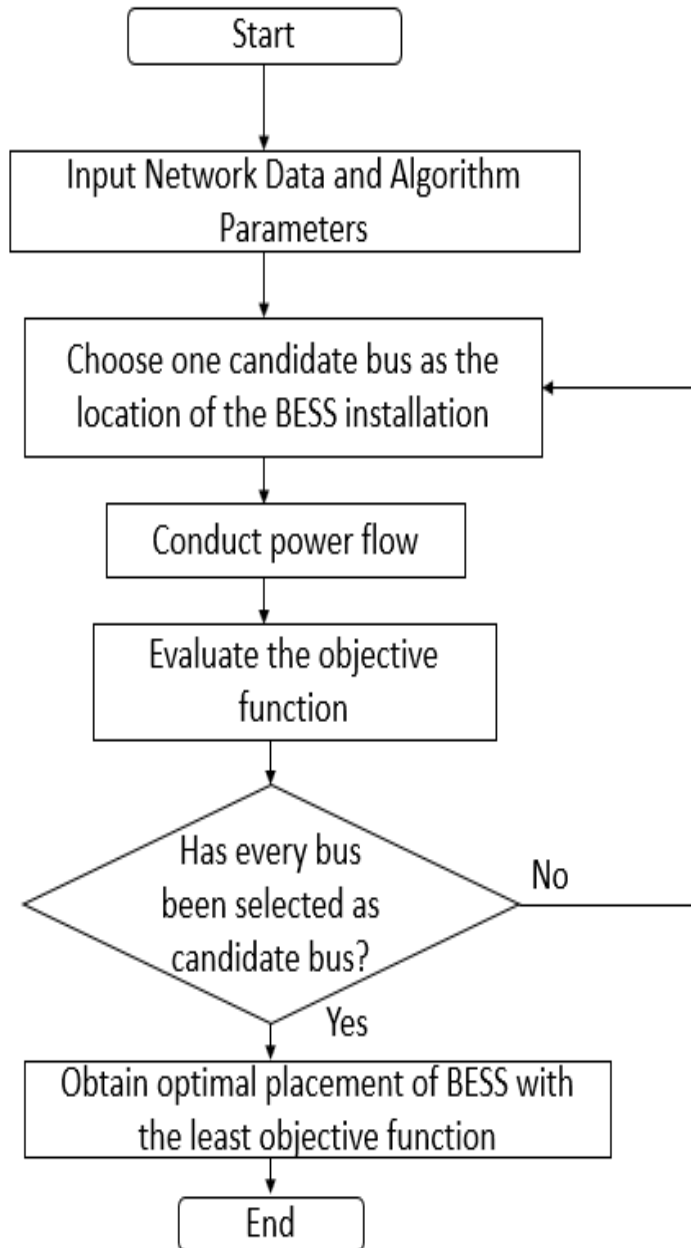


Figure 2.8: A flowchart showing the stages of the optimization.

2.2.3 The test system used for reducing real power losses and mitigation of voltage deviations

The test system for the suggested BESS placement strategy is presented in Figure 2.9. It is an IEEE 33-bus distribution network with a frequency of 60 Hz [36], [37]. The generator details are given in Table 2.9. The Western Cape Network used previously was not suitable for the demonstration of the proposed placement

methodology because the voltage deviations in the buses were within acceptable levels according to the grid codes.

More so, PSO and fmincon were used in this scenario for a comparison between a metaheuristic algorithm and a deterministic algorithm respectively.

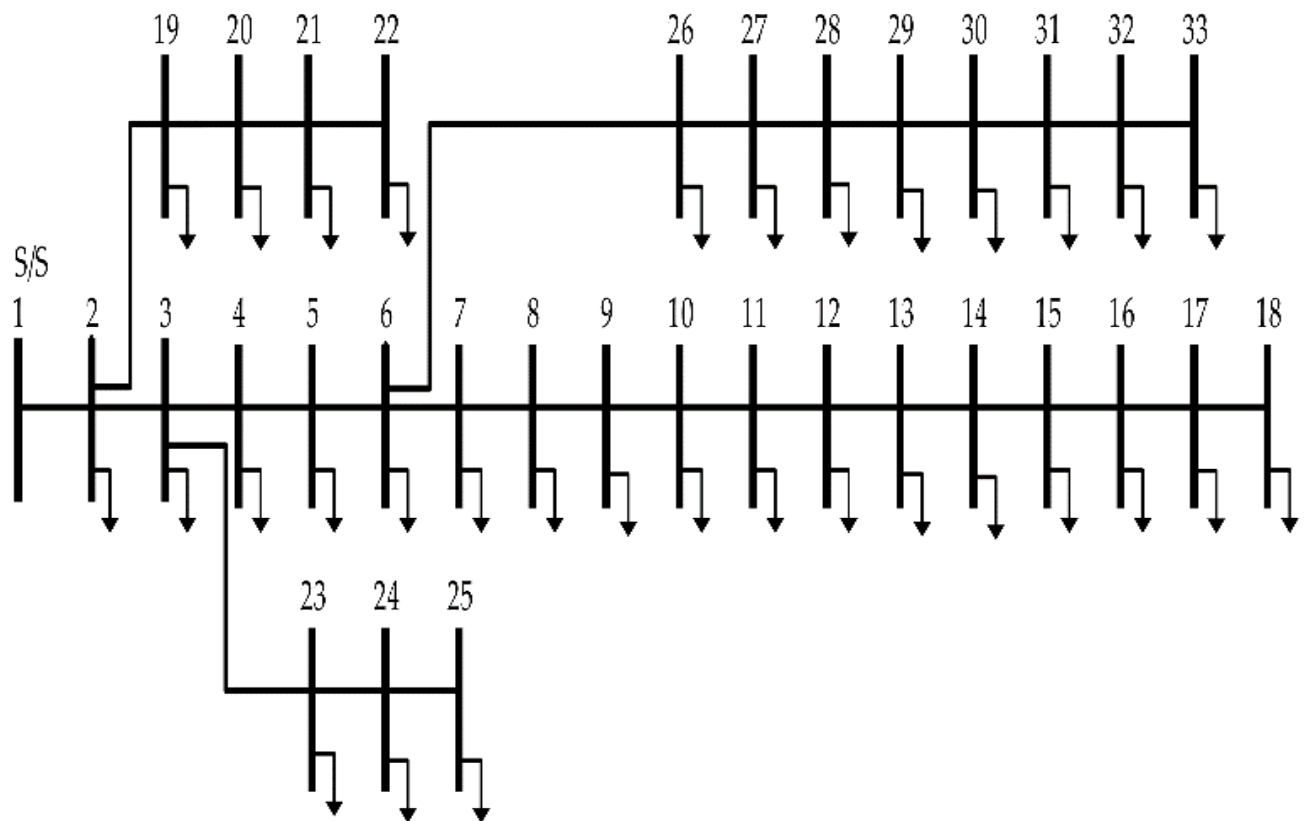


Figure 2.9: One-line representation of the test system [36], [37].

Table 2.9: Generator details

Type	Apparent Power (MVA)	Real Power (MW)	Bus connection
Synchronous generator	4.37	3.72	1
Wind power plant (WPP)	1.11	1.0	18

2.2.4.1 Simulations, results, and discussions (BESS placement for the reduction of real power losses and mitigation of voltage deviations)

The total system costs formulated in equation (2.18) were solved with two optimization solvers: PSO and fmincon. The results are presented in Table 10, with a convergence diagram shown in Figure 2.10. In Table 2.10, priority was given to achieving the lowest system costs. Thus, the priority ranged from 1 to 32, indicating the total system costs obtained from the two optimization solvers.

Table 2.10: Simulation results for total system costs

Bus numbers	Minimum system costs (\$) using PSO	Minimum system costs (\$) using fmincon	Priority
29	247.62	248.66	1
28	258.62	259.08	2
30	265.87	264.23	3
31	272.38	273.13	4
6	288.03	288.79	5
26	290.16	291.91	6
27	296.29	297.04	7
7	308.16	309.04	8
32	313.65	314.03	9
33	326.03	326.41	10
4	370.01	370.88	11
5	374.13	375.07	12
3	410.99	411.27	13
23	452.26	452.54	14
8	460.83	462.08	15
2	493.53	493.81	16
25	530.67	530.95	17
19	534.80	535.08	18
9	545.37	546.75	19
24	576.07	572.22	20
20	617.34	617.62	21
10	627.91	629.26	22
11	659.17	660.68	23
21	699.88	700.16	24
12	709.45	712.07	25
22	741.15	741.43	26
13	824.26	826.13	27
14	865.53	867.40	28
15	948.07	950.04	29

16	1030.60	1032.70	30
17	1154.41	1156.63	31
18	1236.95	1239.29	32

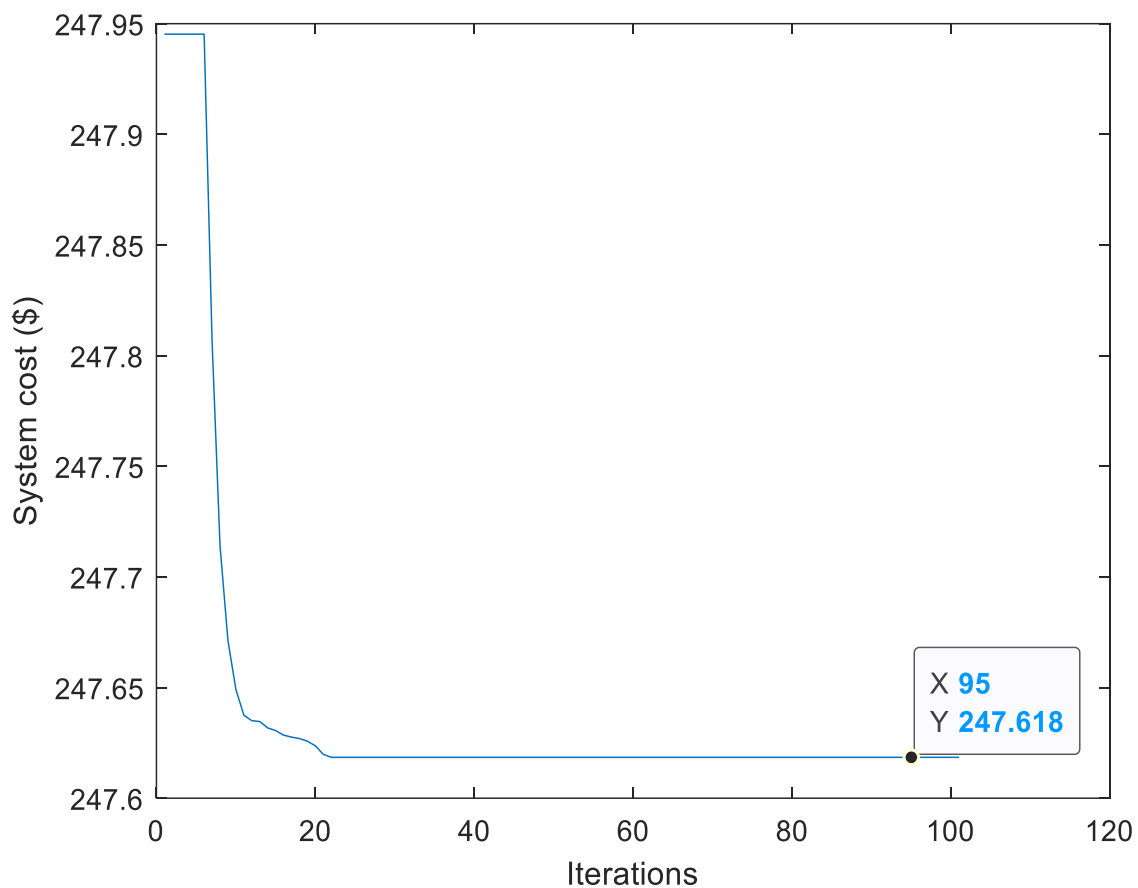


Figure 2.10: Graphic representation of the optimization convergence using PSO (100 iterations)

The focus of the optimization was to determine the bus that produces the lowest system costs. It was evident from Table 2.9 that the lowest system costs were achieved by integrating battery energy storage at bus 29. This is when the system cost was lowest at \$247.62 or \$248.66. Bus 18 proved to be unacceptable with total system costs of \$1236.95 (using PSO) and \$1239.29 (using fmincon).

Additionally, it was found that PSO consistently performed better than fmincon in minimizing the objective function, as shown in Table 2.9.

2.2.4.2 Simulations, results, and discussions (mitigation of real power losses)

To appreciate the capability of BESS for reducing the real power losses in the test system, three scenarios were considered:

- A network without BESS;
- A network with BESS integrated at the optimal location; and
- A network with BESS connected in three non-optimal locations.

Simulations were executed for the three scenarios, and the outcomes are given in Table 2.11.

Table 2.11: Power losses under different network conditions

Distribution network	Power loss (MW)
Without a BESS	0.13
With a BESS in the optimal location	
Bus 29	0.06
With a BESS in non-optimal locations	
Bus 14	0.21
Bus 17	0.28
Bus 18	0.30

From the outcomes of the simulations given in Table 2.10, by installing the BESS at the optimal location (bus 29), the overall power loss in the test system was reduced by over 50% of its initial value (without the BESS). However, BESS locations that were not optimal resulted in an increase in power losses. Hence, to maximize the utilization of a BESS in the grid, it is critical to place it in the optimal location in the network.

2.2.4.3 Simulations, results, and discussions (mitigation of voltage deviations)

The voltage magnitude of every bus in the test system is shown in Figure 2.12. The impact of BESS placement at the optimal location on the voltage level of all buses in the test system is obvious. The bus voltages before and after the installation of the BESS in the optimal location were compared. It was evident that by placing the BESS at bus 29, the voltage levels of all buses were enhanced and were within the allowable limits.

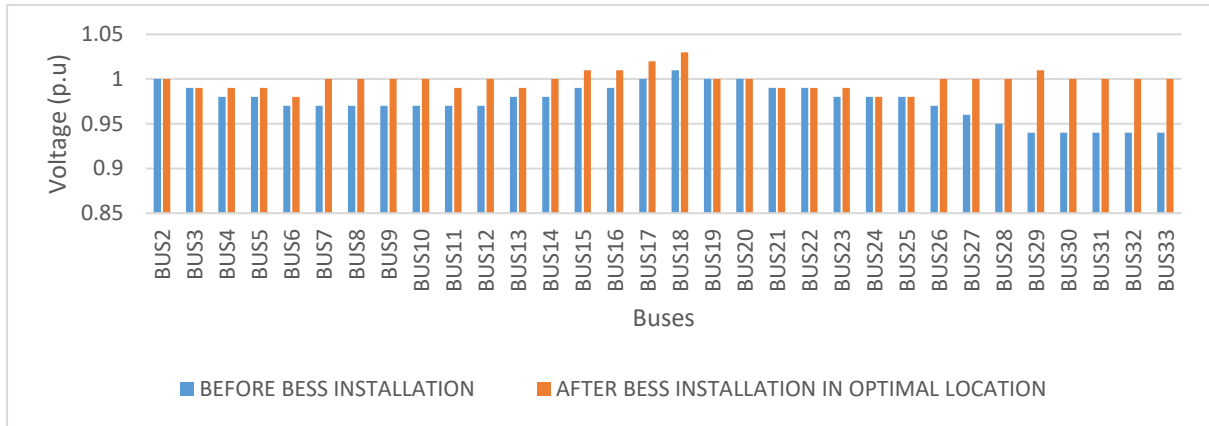


Figure 2.11: Voltage profile improvement through the optimal placement of the BESS

2.3 The most critical parameters influencing BESS placement

The most critical parameters influencing BESS placement depend on the objective of the placement (for example, mitigation of voltage deviations, reduction of power losses, support for the frequency nadir, or improvement of power system voltage stability).

The BESS placements achieved in this study were based on the optimization of a formulated objective function. The results obtained revealed that the BESS position in the network affects the RoCoF (Table 2.5), while Table 2.9 shows how the BESS position in the network affects the system costs, i.e., the costs due to power losses and voltage deviations. Thus, a sensitivity analysis was not conducted to determine the most critical parameters influencing BESS placement. Instead, the most critical parameters influencing BESS placement were determined from the objective of BESS placement. These parameters included the loss sensitivity, costs due to power losses and voltage deviations, RoCoF value, and magnitude of active power injections from energy sources.

In conclusion, the optimization enabled the magnitude of the critical parameters influencing the placement of BESS to be better understood.

2.4 Summary

Methodologies for determining the optimal location of a BESS in a power system network to provide frequency nadir support during contingency events were developed. By using the proposed methods together with optimization algorithms (PSO, GA and fmincon) the optimal location for BESS for frequency support (during contingency events) in the modified 53-bus Western Cape network was

identified. Moreso, the mathematical formulations for finding the optimal location of BESS for the reduction of active power losses and mitigation of voltage deviations were developed. By deploying this with a metaheuristic (PSO) and deterministic (fmincon) algorithms, the best location of BESS in a 33-bus distribution network for the reduction of power losses and mitigation of voltage deviations was known.

Simulation results from the demonstration of the proposed BESS placement methods were presented, and algorithms were compared based on the robustness of their solutions and computational times.

3. OPTIMAL SIZING OF A BESS FOR MULTIPLE FUNCTIONS

To utilize a BESS effectively for multiple applications, first, the capacity must be determined, such that it meets the technical requirements of the multiple functions and also provides economic returns. In this study, a novel method was proposed to determine the optimal size of a BESS for multiple functions. The novel method utilized a regression analysis, the DSO algorithm, and the RoCoF at a specific level of renewable energy integration in the test system. The RoCoF as a result of a significant power mismatch was determined for the test system at varying levels of renewable energy penetration. This was then used to determine the initial size of the BESS for several applications. Thereafter, through a simulation of the scaled sizes of this initial BESS size and the application of a regression analysis, a multi-objective optimization formulation with common variables was developed. A new metaheuristic algorithm, i.e., the DSO algorithm, was then deployed to solve the multi-objective functions, and then the optimal size of the BESS for several applications was evaluated. A detailed description of this novel BESS sizing technique, including the methodology flow chart, is given in subsection 3.2.

3.1 Frequency characteristics of a power system

In a grid network, the relationship between power production and demand determines the response of the system frequency. Under normal power system operating conditions, the power produced must be in equilibrium with the loads and real power losses in the system. However, during frequency disturbances, this equilibrium between the power generated and load demand is lost, and the system frequency will respond accordingly to the nature of the contingency. There are four stages of nominal frequency restoration in a grid network subjected to disturbances that disrupt the equilibrium between generation and load: inertia response, primary frequency control, secondary frequency control, and tertiary frequency control [65], [104], [105]. These phases are shown in Figure 3.1.

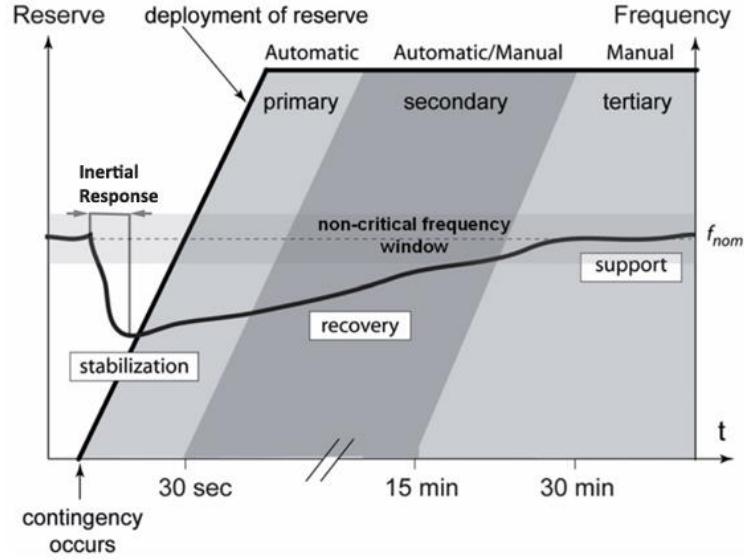


Figure 3.1: The four stages of nominal frequency restoration [49]

First, the inertia response activates as a natural response to halt the decline of system frequency caused by the imbalance between the power supply and demand. This action helps to maintain the frequency nadir within the permissible threshold. Immediately following the inertial response, primary frequency control is implemented to bring the frequency to a steady state, which is typically relieved by the secondary frequency control. Finally, the tertiary control ensures the return of previously assigned generation levels [19].

3.2 Proposed methodology for sizing a BESS for multiple functions.

A novel BESS sizing strategy is proposed in this thesis. Using a regression analysis and the DSO algorithm, the approach enables the capacity of a BESS to be determined for several applications. In several multi-objective optimizations, weighting factors are commonly applied for scalarization and to control the diversity of the solutions [74]-[75]. However, when using this approach, important solutions may be lost, and some objective functions may take dominance over others, resulting in biased solutions. Using the technique proposed in this study, the issues regarding the weighting factors will be completely eliminated in the mathematical formulations through the adoption of a regression analysis. A mutual variable, referred to as the BESS multiplier, will be incorporated in all objective functions. This approach utilizes the concept of a regression analysis to ensure that optimization processes will be controlled and fair, with unbiased solutions.

The suggested novel strategy aims to provide an optimally sized BESS for frequency nadir support (during contingency events), as well as the reduction of real power losses and mitigation of voltage deviations. The various stages in the

methodology are summarized in the eight steps below, with the corresponding flow chart presented in Figure 3.2.

- (1) The frequency response of the test system was determined under different levels of renewable energy penetration. This enabled the appropriate value of RoCoF to be determined and incorporated into the mathematical formulation for the objective function.
- (2) The initial BESS capacity was evaluated based on the inertia constant of the power system according to [65].
- (3) The optimal location for BESS placement for frequency support was determined based on equation (2.9)
- (4) The initial BESS capacity was scaled using several BESS multipliers. Each BESS scaled size was connected to the optimal location identified in step 3. Then, a simulation was conducted to determine the frequency nadir, power losses, and voltage deviations.
- (5) The data sets generated in step (4) were transformed into per-unit values using their base values. The transformation into per-unit values was necessary to reduce the complexity of the calculations and avoid the dominance of specific data sets over others.
- (6) The per-unit data sets in step (5) were validated for linear, logarithmic, and polynomial models to determine the best model fit for the data. These validated models were then used to formulate multi-objective functions using a regression analysis.
- (7) Metaheuristic optimization algorithms were then used to solve the objective functions developed in step (6).
- (8) The optimal BESS multiplier was selected and the optimal BESS size was determined for multiple functions.

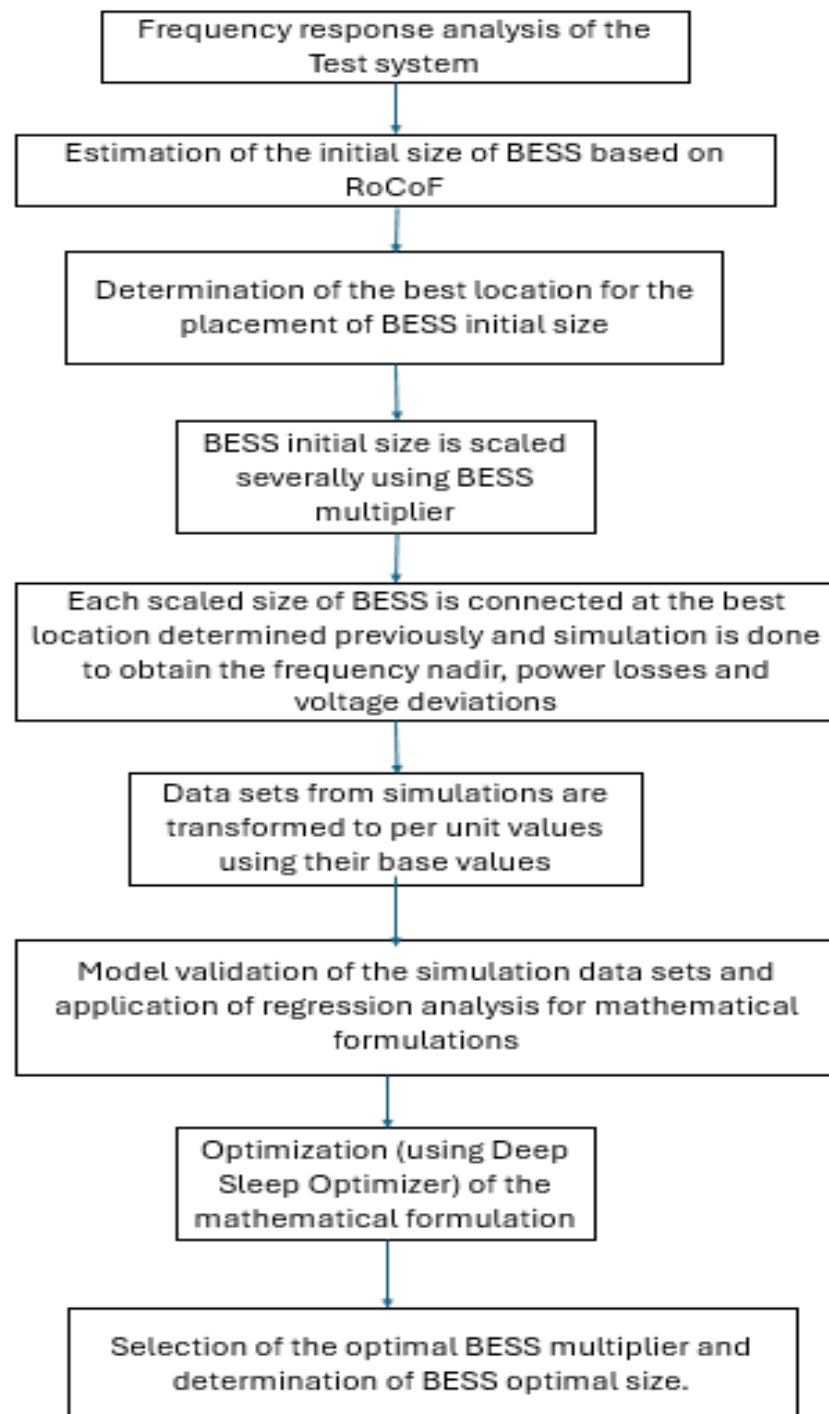


Figure 3.2: Flowchart of the BESS sizing methodology

The first step in the sizing methodology was to determine the RoCoF at varying degrees of renewable energy penetration. This would provide appropriate technical guidance on the level of renewable energy penetration to be adopted for the determination of the optimal BESS size for multiple functions. Hence, the

initial BESS size was estimated using the network parameters according to Okafor and Folly [19] and Knap et al. [65]. The determination of the initial BESS size was followed by a determination of its most appropriate position for connection into the test system using the method presented in section 2.1.1. Then, several scaled sizes of the initial BESS size were produced by deploying a battery energy storage multiplier. The next step involved the successive integration of each scaled size into the initially determined optimal location. Thereafter, the simulation of the test system proceeded. The required data were the real power losses, frequency nadirs, and average voltage deviations. These data sets were converted into their corresponding per-unit equivalents. They each underwent a process of validation to ascertain the model that each data set represented. Once the validation process was completed, formulations of suitable relationships among the variables were achieved, resulting in multi-objective optimization functions relating to power losses, frequency nadirs, and voltage deviations with the BESS multiplier. Thereafter, a new metaheuristic framework was deployed to determine the optimal BESS size for the required applications.

3.3 Test system for establishing the sizing methodology

3.3.1 Description of the test system

A BESS sizing methodology was formulated to ensure that the multiple functions of frequency support (during contingency), reduction of real power losses, and mitigation of voltage deviations were implemented. Therefore, a single network suitable for the three functions was required. The IEEE 33-bus, which was used previously, could not be used because it is a distribution network and could not be used to demonstrate frequency regulation. The previously used Western Cape transmission network was also not suitable because the voltage deviations in the network were within acceptable limits. Therefore, it could not serve as a robust test model for testing voltage deviations. The IEEE-39-bus transmission network [72] (shown in Figure 3.3) was therefore selected as a suitable test system for the proposed sizing methodology. The normal frequency of the network was 60 Hz and the allowable bounds for the frequency were 59.7 Hz (lower bound) and 60.3 Hz (upper bound), based on Okafor and Folly [72] and National Grid Electricity Transmission [106]. The network data was obtained from the literature [26], [27], [107]. The generation units consisted of ten alternating current generators (G1–G10) and five wind power plants (WPP1–WPP5). Table 3.1 presents details of the generation units

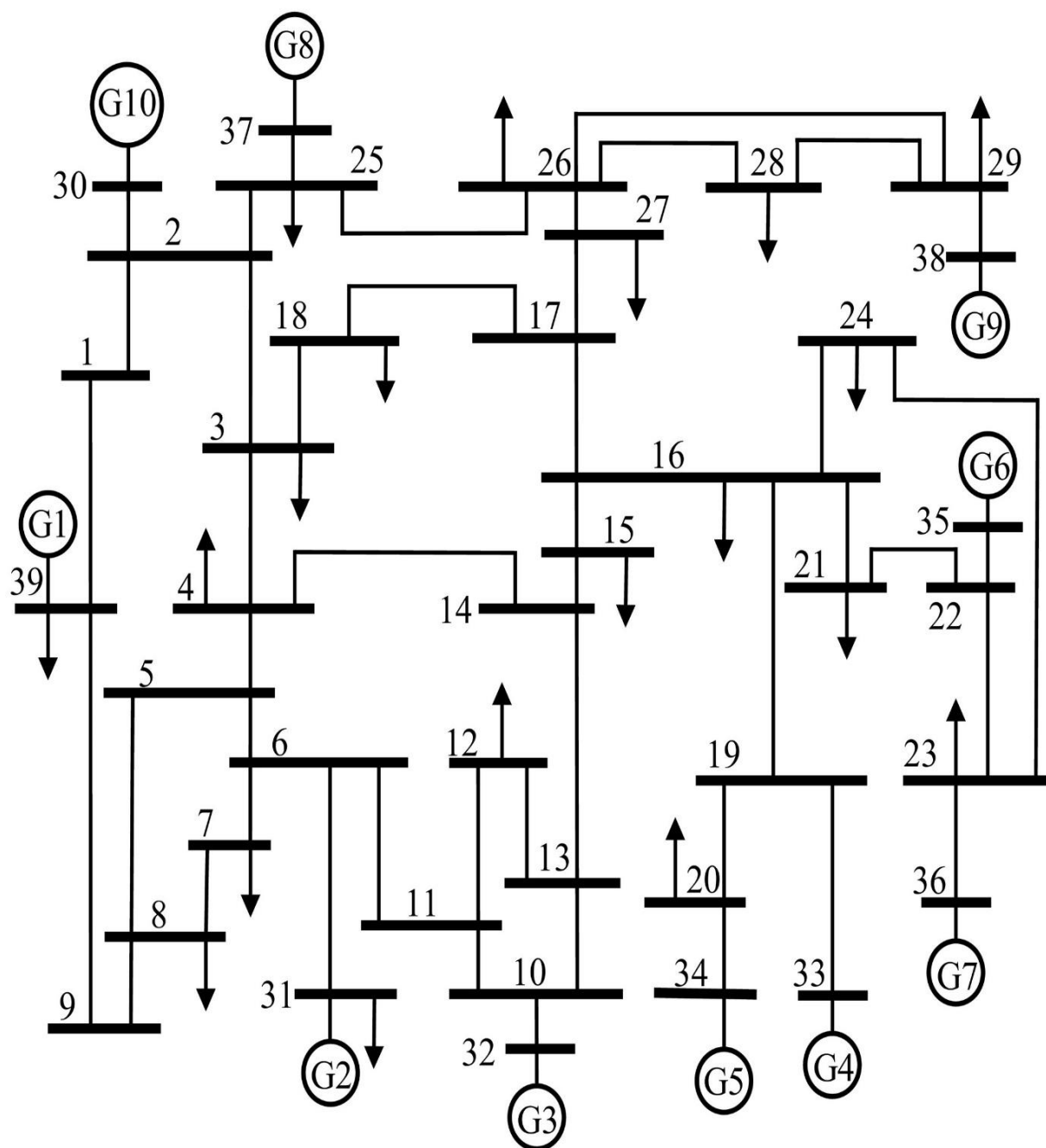


Figure 3.3: Test system for the sizing methodology [72]

Table 3.1: Summary of the generation units in the modified IEEE 39-bus network

Generator	Capacity (MVA)	Capacity (MW)	Units	Bus connection of
G1	520	450	2	39
G2	500	450	1	31
G3	700	650	2	32
G4	700	632	2	33
G5	330	254	1	34
G6	300	247	1	35
G7	600	500	1	36
G8	600	540	2	37
G9	600	560	2	38
G10	400	250	2	30
WPP1	700	650	2	32
WPP2	600	540	2	37
WPP3	700	500	2	30
WPP4	600	450	2	34
WPP5	500	403	2	16

3.3.2 Examination of the test system's frequency behavior under contingency conditions

The behavior of the test system during a power system disturbance was investigated. The aim was to determine how the RoCoF changed during a contingency event as the grid penetration of renewable energy increased in the network. This is crucial for determining the appropriate size of a BESS that could adequately provide frequency nadir support during contingencies in a network with a high renewable energy penetration [27]. To conduct a frequency analysis using the test system, the network was modeled to accommodate the different grid penetrations of renewable energy investigated in the study. A single large outage (700 MVA, 500 MW) was triggered. The values of the lowest frequency attained and the corresponding RoCoF for each level of renewable energy penetration are presented in Table 3.2, while the response plots for these frequencies are shown in Figure 3.4.

Table 3.2: Proportion of wind power grid penetration and frequency parameters

Level of wind power grid penetration (%)	Frequency nadirs (Hz)	RoCoF (Hz/s)
0	59.60	-0.3707
10	59.57	-0.4166
20	59.56	-0.4761
30	59.43	-0.4945
40	59.26	-0.5233
50	59.15	-0.5579

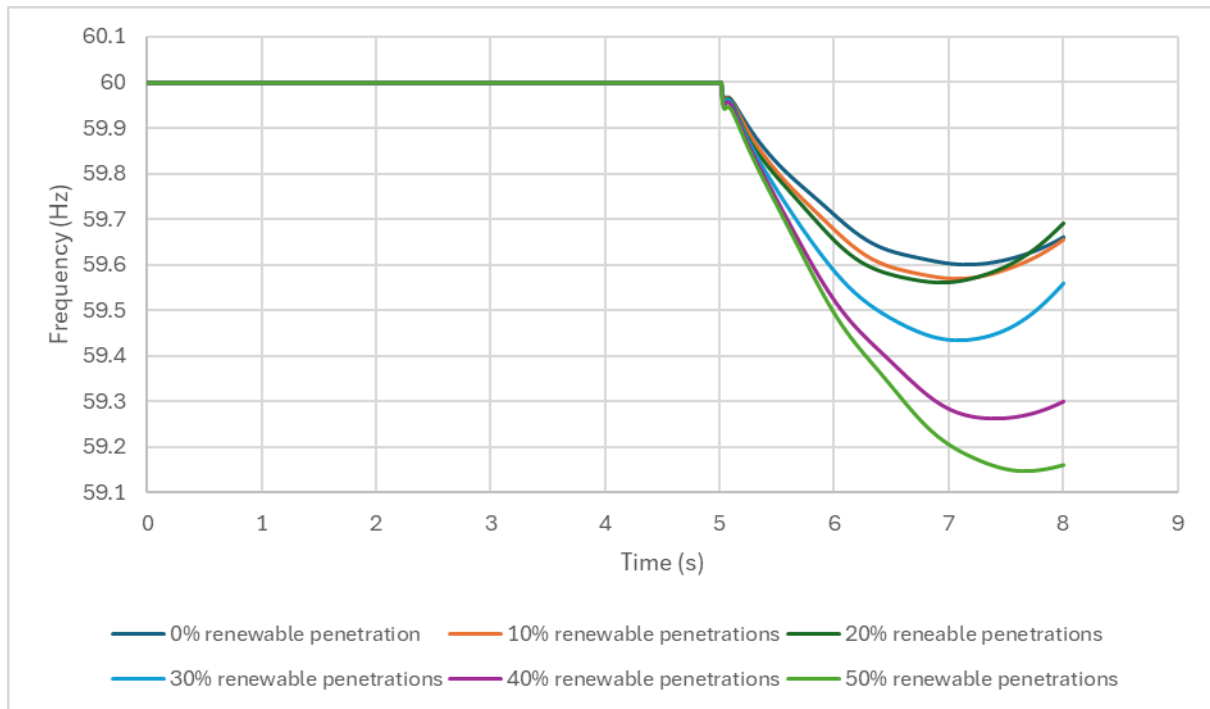


Figure 3.4: Frequency response plots for different levels of renewable energy penetration

3.3.3 The BESS model for frequency support during power system frequency events.

The BESS sizing methodology proposed here utilizes the BESS model created by DIgSILENT [27]. Many authors have previously applied this model in studies of frequency stability [108]-[109]. The model has four sub-units[110]-[111].

The battery model is lithium-ion based with double polarization. Double polarization involves the incorporation of ohmic and concentration polarization in battery modeling. The ohmic polarization occurs as a result of the resistance in the electrolyte, separators, and electrodes, while the concentration polarization is

due to the diffusion limitations present in the electrolyte [112]. The inclusion of double polarization in battery modeling enables a more accurate prediction of its performance, SoC estimation, and the optimal thermal management strategy [113]-[115]. The details of the battery model have been reported by Alsharif et al. [24].

The frequency controller regulates the magnitude of real power that will be released into the network (for a load increase contingency) or absorbed from the network (as a result of a load decrease contingency). It is droop-based, and the parameters used were reported by Nuhic and Yang [110].

The algorithms that determine if the BESS will charge or discharge are contained in the charge controller. The charge controller also ensures that there are no violations of the SOC conditions.

The PQ controller manages the flow of real and reactive power. It operates in the dq reference frame and deploys PI controllers to achieve the goal of real and reactive power control. All parameters used in building the BESS model for frequency support during contingency were reported by DIgSILENT Power Factory [109].

3.3.4 The DSO optimization algorithm

The BESS sizing approach proposed in this thesis used the DSO, a recently introduced metaheuristic optimization method, and the results were compared with a traditional metaheuristic algorithm (i.e., the GA) to authenticate the results. A comparison between DSO and other metaheuristic algorithms was conducted and is reported in section 1.3 (Table 1.2). In this section the DSO is compared with hybrid optimization methods comprising both metaheuristic and deterministic algorithms, as presented in Table 3.3.

Table 3.3: Comparison between the DSO and hybrid optimization methods (heuristic and deterministic) [56], [116]-[117]

Features	DSO (metaheuristic)	Hybrid algorithm (metaheuristic and deterministic)
Exploration/exploitation	Balanced, uses a rapid eye movement (REM) phase for exploration and deep sleep for exploitation.	Achieves balance by blending deterministic and heuristic algorithms.

Convergence speed	Generally fast as a result of the adaptive sleep cycle operator.	Can be faster if the local optima are refined using a deterministic algorithm.
Implementation complexity	Easy to implement based on the constant sleep-based rule.	Higher complexity. Requires the switching of logic between deterministic and metaheuristic algorithms.
Computational costs	Low, the deep sleep mechanism reduces unnecessary evaluations.	High as a result of overheads from deterministic computations.
Robustness to local optima	High as a result of the sleep-phase-based randomization.	May be higher if well designed. Otherwise, may be trapped in local optima.

The DSO is a recently proposed metaheuristic optimization technique inspired by the human sleep pattern. To solve optimization problems, it mimics the sleep–wake cycle [47]. The DSO method has its mathematical roots in the dual-progression paradigm of sleep control, which relies on homeostatic and circadian mechanisms [118]-[120]. When a person is awake, the homeostatic process grows exponentially, and when they are sleeping, it diminishes at a similar rate. The circadian process, meanwhile, governs the conclusion of the sleep cycle [121]-[123].

An agent (representing an individual) progressively enters an unconscious condition at the start of the sleep cycle. This phase is referred to as "falling into the hole." Sleep is eventually brought on by the reduction of homeostatic pressure during this phase. The degree of this pressure decrease has a huge influence on the standard of sleep. To identify the best global solution for a particular problem, the DSO algorithm explores a search space. Homeostatic pressure increases throughout this process, simulating the wake phase of the sleep cycle. The agent mimics the dynamics of the human sleep–wake process by updating its position and fitness at each iteration of the sleep–wake cycle. These updates act as reference points for the next agent.

The operational phases of DSO consist of population initialization, sleep phases, and memory consolidation [56]. For population initialization, a set of candidate solutions is randomly initialized within a search space. The DSO sleep cycles exist in three stages: the light sleep, deep sleep, and rapid eye movement (REM) phase. In the light sleep phase, there is random exploration leading to the avoidance of local minima. The deep sleep phase ensures memory consolidation, which enhances local searches around good solutions. The REM phase is

associated with stochastic exploration of new regions and the diversification of solution paths to avoid stagnation. The search behavior of the DSO algorithm is adjusted through tunable parameters such as the sleep power index, wake power index, and maximum sleep duration [56].

During DSO operation, an agent is only allowed to be in either the sleep or wake states within the sleep–wake cycle. Equations (3.2) and (3.3) for the sleep and wake state provide homeostatic pressure at a specific time (t) according to Skeldon et al. [123]:

$$\mathcal{H}(t) = \mathcal{H}_0(t) \cdot e^{(t_0-t)/X_s} \quad (3.1)$$

$$\mathcal{H}(t) = \mu(t) + (\mathcal{H}_0(t)) - (\mu(t)) \times (e^{(t_0-t)/X_w}) \quad (3.2)$$

where X_s and X_w are the sleep power index and wake power index, respectively; $\mathcal{H}_0(t)$ is the initial homeostatic pressure at time t_0 ; $\mu(t)$ is the “wake” or “sleep” threshold, $\mu(t) = 0$ if the agent is in the sleep state and $\mu(t) = 1$ if the agent is in the awake state. $\mathcal{H}(t)$ must lie between the maximum, $\mathcal{H}(t)^{max}$ and the minimum homeostatic pressure $\mathcal{H}(t)^{min}$, as in equations (3.3) and (3.4), respectively:

$$\mathcal{H}(t)^{max} = \mathcal{H}_{(0)}^+ + a c(t) \quad (3.3)$$

$$\mathcal{H}(t)^{min} = \mathcal{H}_{(0)}^- + a c(t) \quad (3.4)$$

where $c(t)$ is the circadian periodic function; a is the circulatory cost per unit function; and $\mathcal{H}_{(0)}^+$ is the highest starting value of homeostatic pressure, while:

$$c(t) = \sin\left(\frac{2\pi}{T}(t - \alpha)\right) \quad (3.5)$$

where α is a variable that is randomly distributed, with values lying between 0 and 1 and representing the circadian time shift. Equation (3.6) provides the starting homeostatic pressure:

$$\mathcal{H}_0(t) = \gamma + r(X_{best} - \mu(t) \cdot X_{mean}) \quad (3.6)$$

where X_{mean} is the agents' mean homeostatic value; X_{best} is the best option for agents who are deeply asleep; γ is the initial population of the agents; and R is a distributed random vector in $[0,1]$.

The DSO algorithm supersedes other metaheuristic algorithms (PSO and GA) in terms of its capability to avoid local optima (due to its reset mechanism) and faster convergence speed. The main challenge for the DSO is that it is a new

algorithm that has only been applied in a few studies; hence, few comparisons are available. The DSO codes (in MATLAB) are provided in Appendix 8.2, while the metrics are given in Table 3.4.

It is important to note that the homeostatic values in the DSO parameters play a key control mechanism in DSO operations. By increasing it, the agent has a high tendency to go into “a deep sleep”, thereby performing local search around already known good solutions. However, by decreasing it, the agents more actively search the global solution space. The DSO parameters presented in Table 3.4 are based on the literature.

Also, it is evident from Table 3.4 that more agents (500) and iteration number (1000) have been chosen for this scenario as compared to PSO and GA previously used. This is necessary to generate more complete (wider) and refined pareto fronts in the multi-objective optimization. However, there may be high risks of increased computation time and higher computational costs.

Table 3.4: The DSO metrics

Parameter	Value	Parameter	Value
Minimum homeostatic value	0.17	Maximum sleep duration of an agent	24
Maximum homeostatic value	0.85	Number of agents	500
Circadian cost per unit function	0.1	Maximum iteration	1000
Wake power index	18.2	Lower boundary	0.05
Sleep power index	4.2	Upper boundary	1.05

The GA was described in section 2.1.6. Its metrics for identifying the optimal size of a BESS for multiple applications are given in Table 3.5.

Table 3.5: The GA metrics for the optimal sizing of a BESS

Parameter	Value
Population size	500
Crossover probability	0.80
Mutation probability	0.20
Acceleration factor	2.05

Maximum iteration	1000
-------------------	------

3.4 The fundamentals of the regression analysis.

Regression analysis has been used to analyze highly complex engineering networks [124]. The technique can determine possible associations between variables. The regression analysis framework upholds that errors associated with the regression lines are normally distributed, and therefore, a least squares analysis can be applied to determine the best fit [125]-[127]. Regression analysis is widely used in fitting curves to data sets, providing a robust framework for modelling relationships between variables [128].

In a data set (X_i, Y_i) , where X_i = the input variable and Y_i = the output variable, the techniques of regression and application of the data set in equation (3.7) could be developed as a linear model [129]:

$$Y_i = \beta_0 + \beta_1 X_i \quad (3.7)$$

where:

$$\beta_1 = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^n (X_i - \bar{X})^2} \quad (3.8)$$

$$\beta_0 = \bar{Y} - \beta_1 \bar{X} \quad (3.9)$$

Also:

$$x_i = X_i - \bar{X} \quad (3.10)$$

$$y_i = Y_i - \bar{Y} \quad (3.11)$$

$\bar{X}$ and $\bar{Y}$ are representations of the sample means.

Equations (3.8), (3.10), and (3.11), could be re-arranged using appropriate substitutions to obtain equation (3.12):

$$\beta_1 = \frac{\sum_{i=1}^n x_i y_i}{\sum_{i=1}^n x_i^2} \quad (3.12)$$

Applying the concepts of the sum of squares and sum of products according to Seber and Wild [125] and Bevington et al. [129]:

$$\sum_{i=1}^n (x_i^2) = \sum_{i=1}^n (X_i^2) - \frac{(\sum_{i=1}^n X_i)^2}{n} \quad (3.13)$$

$$\sum_{i=1}^n (x_i y_i) = \sum_{i=1}^n (X_i Y_i) - \frac{(\sum_{i=1}^n X_i)(\sum_{i=1}^n Y_i)}{n} \quad (3.14)$$

With the number of samples represented as n , equation (3.15) could be developed from equation (3.12) by substituting equations (3.13) and (3.14).

$$\beta_1 = \frac{\sum_{i=1}^n (X_i - Y_i) - \frac{(\sum_{i=1}^n X_i)(\sum_{i=1}^n Y_i)}{n}}{\sum_{i=1}^n (X_i^2) - \frac{(\sum_{i=1}^n X_i)^2}{n}} \quad (3.15)$$

β_0 and β_1 were determined from equations (3.9) and (3.15), respectively.

However, the given data set may represent a second-order polynomial model as given in equation (3.16):

$$Y_i = a + bX_i + cX_i^2 \quad (3.16)$$

In such a scenario, to evaluate the constants, a , b , and c the concept of the least square is deployed [129]. The least squares strategy focuses on minimizing the goodness of fit (χ^2) of a given data representation [129]. With a given data set X_i , Y_i , the goodness of fit is determined using equation (3.17), as reported by Seber and Wild [125]:

$$\chi^2 = \sum \frac{\Delta Y_i^2}{\sigma_i^2} = \sum \frac{1}{\sigma_i^2} (Y_i - a - bX_i - cX_i^2)^2 \quad (3.17)$$

where σ_i^2 is the weighting factor.

Equations (3.18) to (3.20) are used to determine the least value of χ^2 :

$$\frac{\partial \chi^2}{\partial a} = -2 \sum \frac{1}{\sigma_i^2} (Y_i - a - bX_i - cX_i^2) = 0 \quad (3.18)$$

$$\frac{\partial \chi^2}{\partial b} = -2 \sum \frac{X_i}{\sigma_i^2} (Y_i - a - bX_i - cX_i^2) = 0 \quad (3.19)$$

$$\frac{\partial \chi^2}{\partial c} = -2 \sum \frac{X_i^2}{\sigma_i^2} (Y_i - a - bX_i - cX_i^2) = 0 \quad (3.20)$$

Simplifying equations (3.18) to (3.20), produces equations (3.21) to (3.23):

$$\sum Y_i = a \sum 1 + b \sum X_i + c \sum X_i^2 \quad (3.21)$$

$$\sum X_i Y_i = a \sum X_i + b \sum X_i^2 + c \sum X_i^3 \quad (3.22)$$

$$\sum X_i^2 Y_i = a \sum X_i^2 + b \sum X_i^3 + c \sum X_i^4 \quad (3.23)$$

Note that the number of sample data points is represented as $\sum 1$. By simultaneously solving equations (3.21) to (3.23), the constants a , b , and c can be found, and the second-order polynomial is determined. The data set provided may represent a third-order polynomial model. The procedure to follow for a third-order polynomial model is given in equation (3.24):

$$Y_i = a + bX_i + cX_i^2 + dX_i^3 \quad (3.24)$$

where:

$$\sum Y_i = a\sum 1 + b\sum X_i + c\sum X_i^2 + d\sum X_i^3 \quad (3.25)$$

$$\sum X_i Y_i = a\sum X_i + b\sum X_i^2 + c\sum X_i^3 + d\sum X_i^4 \quad (3.26)$$

$$\sum X_i^2 Y_i = a\sum X_i^2 + b\sum X_i^3 + c\sum X_i^4 + d\sum X_i^5 \quad (3.27)$$

$$\sum X_i^3 Y_i = a\sum X_i^3 + b\sum X_i^4 + c\sum X_i^5 + d\sum X_i^6 \quad (3.28)$$

Equations (3.25) to (3.28) could be solved (using MATLAB codes for the regression analysis in Appendix 8.3) for the determination of the constants. The third-order polynomial is then developed according to equation (3.24).

3.5 Determination of the initial capacity of the BESS and its position in the grid

3.5.1 Determination of the initial capacity of the BESS

The initial size of the BESS ($BESS_{initial}$) for frequency nadir support during a contingency event could be determined from equation (3.29) [42], [65].

$$BESS_{initial}(\text{MW}) = \frac{(H_{target} - H_{PS1})(S_{PS1})}{H_{BESS} - H_{target}} \quad (3.29)$$

where S_{PS1} is the MVA of the test network; H_{target} is an inertia constant at the target change in power; H_{PS1} is the total inertia constant of the grid; and H_{BESS} is the artificial inertia supplied by the BESS. At the assumed inertia constant, the change in power could be evaluated using equation (3.30) [65]:

$$\left(\frac{2H_{target}}{f_0}\right) \times \left(\frac{df}{dt}\right) = \frac{\Delta P}{S_{PS1}} \quad (3.30)$$

where f_0 is the grid frequency; $\frac{df}{dt}$ is the RoCoF; and ΔP is the change in real power. H_{PS1} is the sum of the inertia constant of the grid, which is found using equation (3.31):

$$H_{PS1} = \frac{\sum_{i=1}^n H_i S_i}{S_{PS1}} \quad (3.31)$$

where H_i and S_i are the inertia constant and MVA rating of the i th synchronous machine respectively. H_{BESS} is estimated using equation (3.32) [42].

$$H_{BESS} = 1.736 \times 10^4 \Delta P^{-1.156} \quad (3.32)$$

S_{PS1} , H_{target} , H_{PS1} , and H_{BESS} are calculated as 8350 MVA, 3.67 s, 3.56 s, 13.17 s, respectively. Using these calculated values in equation (3.29) the initial capacity of BESS was found to be 96.68 MW.

Thus, $BESS_{initial}$ was 96.68 MW.

3.5.2 The appropriate location for the BESS with this initial capacity.

To determine the most appropriate position for the installation of the BESS with this calculated initial capacity within the modified IEEE 39-bus network [64], the problem formulation for determining the optimal location for a BESS in a grid network described in section 2.1.1 was adopted. The required mathematical formulation is given in equation (2.8) and the optimization constraints are given in equations (2.9) to (2.12). The optimal location for the BESS with an initial capacity of 96.68 MW in the test system was found to be bus 39 and the nadir was 59.6 Hz. Without the BESS, the frequency fell to 59.46 Hz. The worst location was found to be bus 36, with a frequency nadir of 59.38 Hz.

3.6 Simulations

3.6.1 Development of data sets for use in regression analysis formulations.

The data sets required for use in regression analysis formulations were generated through simulations using DIgSILENT software. The required data variables were frequency nadir (Fnadir), real power losses (Plosses), and average voltage deviation (Vd).

With the help of the BESS multiplier, the initial capacity of the BESS was scaled down severely according to equation (3.33). The simulation was implemented using each of the scaled sizes, and the outcomes are given in Table 3.6.

The real loss when no BESS was connected was 65.3 MW

The estimated size of the BESS ($BESS_{initial}$) was 96.68 MW

The normal frequency of the grid was 60 Hz

The reference voltage of each bus was 1.0 pu

The BESS scaled size = $(BESS_{initial}) \times \text{BESS multiplier } (\lambda_{BESS})$ (3.33)

The BESS optimal size = $(\lambda_{BESSopt}) \times (BESS_{initial})$ (3.34)

This is where the BESS multiplier has its optimal capacity $(\lambda_{BESSopt})$.

Table 3.6: Simulation data for the regression analysis

BESS multiplier (λ_{BESS})	BESS scaled size (MW)	Minimum frequency (Fnadir in Hz)	Power losses (Plosses in MW)	Average voltage deviation (Vd in pu)
0.10	9.6680	59.1778	65.05	0.03180
0.20	19.3360	59.2044	64.80	0.02974
0.30	29.0040	59.2271	64.55	0.02769
0.40	38.6720	59.2467	64.31	0.03026
0.50	48.3400	59.2642	64.08	0.03051
0.60	58.0080	59.2792	63.85	0.03126
0.70	67.6790	59.2930	63.63	0.03162
0.80	77.3440	59.3032	63.41	0.03182
0.90	87.0120	59.3121	63.20	0.03167
0.95	91.8460	59.3162	63.10	0.03167
1.10	106.3480	59.3258	62.80	0.03154
1.20	116.0160	59.3305	62.61	0.03059
1.30	125.6840	59.3335	62.43	0.03128
1.40	135.3520	59.3353	62.25	0.03131
1.50	145.0200	59.3358	62.07	0.03115
1.60	154.6880	59.3366	61.91	0.03131
1.70	164.3500	59.3369	61.75	0.03205
1.80	174.0240	59.3377	61.59	0.03151
1.90	183.6920	59.3451	61.44	0.03146
1.95	188.5260	59.3477	61.37	0.03146

The data sets provided in Table 3.6 for power losses and frequency nadir were converted into equivalent per-unit values using their base values. This helped to reduce the complexity of the calculations. The simulation results in per-unit values are given in Table 3.7

Table 3.7: Simulation data for regression formulation in per-unit values

BESS multiplier (λ_{BESS})	Minimum frequency (Fnadir in pu)	Power losses (Plosses in pu)	Average voltage deviation (Vd in pu)
0.10	0.986297	0.996172	0.03180
0.20	0.986740	0.992343	0.02974
0.30	0.987120	0.988515	0.02769
0.40	0.987445	0.984839	0.03026
0.50	0.987737	0.981317	0.03051
0.60	0.987987	0.977795	0.03126
0.70	0.988217	0.974426	0.03162
0.80	0.988387	0.971057	0.03182
0.90	0.988535	0.967841	0.03167
0.95	0.988603	0.966309	0.03167
1.10	0.988763	0.961715	0.03154
1.20	0.988842	0.958806	0.03059
1.30	0.988892	0.956049	0.03128
1.40	0.988922	0.953292	0.03131
1.50	0.988930	0.950536	0.03115
1.60	0.988943	0.948086	0.03131
1.70	0.988948	0.945636	0.03205
1.80	0.988896	0.943185	0.03151
1.90	0.989085	0.940888	0.03146
1.95	0.989128	0.939616	0.03146

3.6.2 Problem formulation for Fnadir, Vd, and Plosses using regression analysis.

The data sets obtained from the simulation and converted to per-unit values for Fnadir, Plosses, and Vd are given in Table 3.6. The validation process for the best model representation of the data sets was achieved using two functions in the Excel software: scatter plot and R^2 . The models investigated for the validation were linear, logarithmic, and polynomial. The sets of data given in Table 3.6 were screened to determine if there was an association between the input variables (independent variables) and the output variables (dependent variables) using scatter plots. Thereafter, the co-efficient of determination (R^2) function in Excel was used to confirm the appropriate model for the data sets. The R^2 value measures how well a model fits a data set. [130]-[131]. An R^2 value of one signifies a perfect fit, while an R^2 value of zero indicates a poor fit [130]-[131].

The output variables (dependent variables) were Fnadir, Vd, and Plosses, while the independent variable was the BESS multiplier (λ_{BESS}). The validation results are presented in Table 3.8.

Table 3.8: Validation of the appropriate model for each data set (R² values)

Model	Fnadir (R ² values)	Plosses (R ² values)	Vd (R ² values)
Linear	0.8200	0.9933	0.2910
Logarithmic	0.9804	0.9091	0.3119
Polynomial	0.9847	0.9995	0.3799

The results presented in Table 3.7 confirmed that the model that best fitted the data sets was a third-order polynomial. The results also revealed a poor fitting for the voltage deviation. The regression equations (3.25–3.28) with MATLAB codes provided in Appendix 8.3 were deployed along with the data sets in Table 3.6. The resulting polynomial equations are given in equations (3.35) to (3.37), and their graphical representations are given in Figure 3.5 to Figure 3.7. The polynomial plot for the voltage deviation in Figure 3.7 shows that a better fit was likely if more data sets with a BESS multiplier greater than 2 were plotted.

$$\text{Fnadir} = 0.9858 + 0.0054\lambda_{BESS} - 0.003\lambda_{BESS}^2 + 0.0001\lambda_{BESS}^3 \quad (3.35)$$

$$\text{Ploss} = 1.0002 - 0.0405\lambda_{BESS} + 0.0052\lambda_{BESS}^2 - 0.0002\lambda_{BESS}^3 \quad (3.36)$$

$$\text{Vd} = 0.0292 + 0.0037\lambda_{BESS} - 0.0019\lambda_{BESS}^2 + 0.0003\lambda_{BESS}^3 \quad (3.37)$$

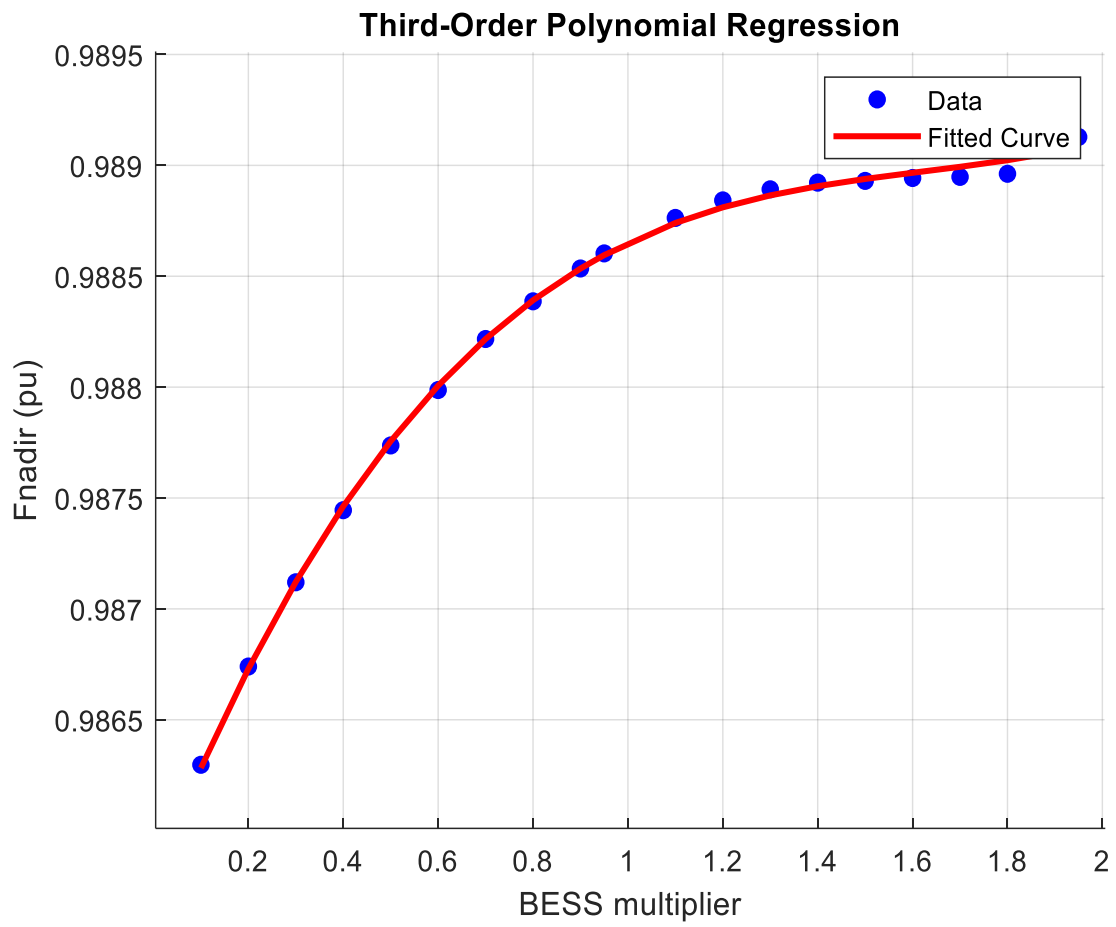


Figure 3.5: The relationship between Fnadir and the BESS multiplier

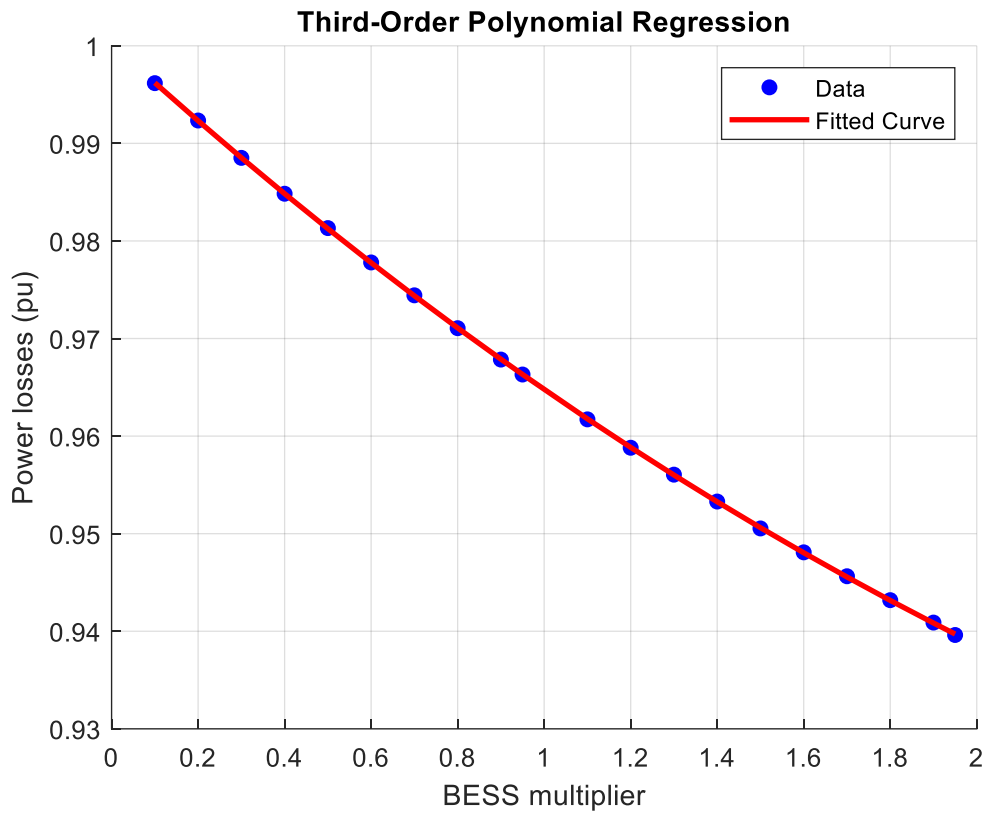


Figure 3.6: The relationship between Plosses and the BESS multiplier

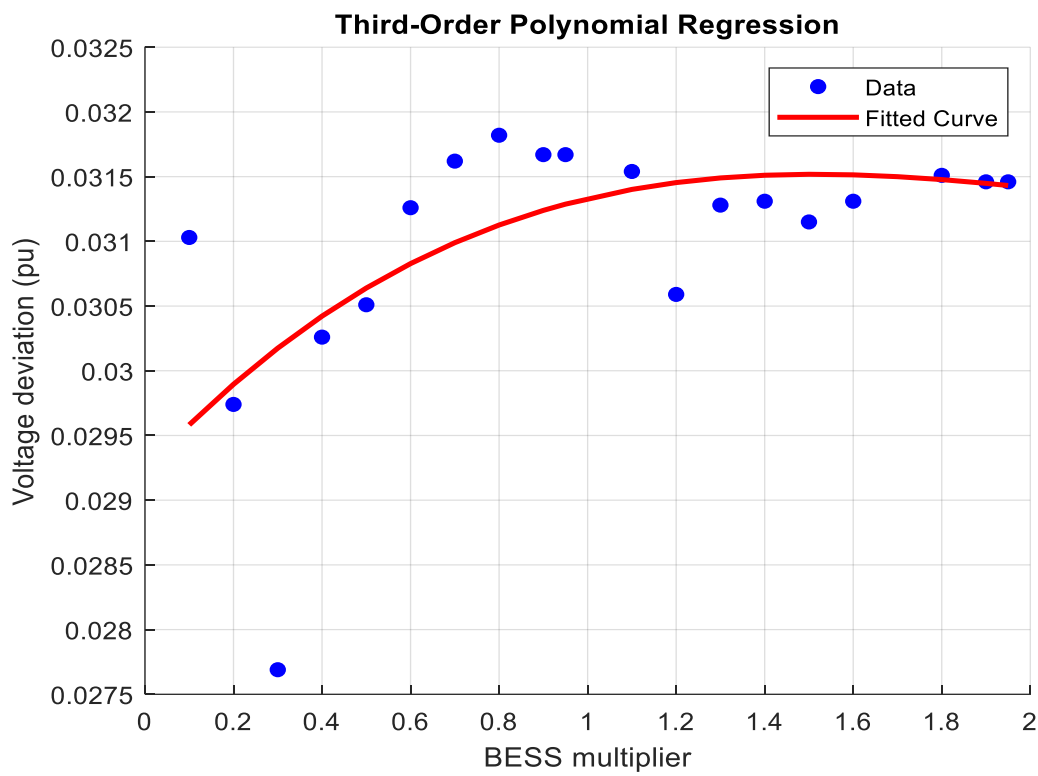


Figure 3.7: The relationship between Vd and BESS multiplier.

3.6.3 Deployment of the DSO and GA algorithms.

The DSO and GA were deployed to determine the optimal BESS multiplier ($\lambda_{BESSopt}$) that satisfied equations (3.35) to (3.37).

The optimization processes were regulated by two main constraints, namely the frequency and voltage constraints in per-unit values given in equations (3.38) and (3.39), respectively:

$$0.9917 \leq f \leq 1.0083 \quad (3.38)$$

where f is the system frequency, and:

$$0.95 \leq V \leq 1.05 \quad (3.39)$$

where V is the bus voltage.

The DSO codes are provided in Appendix 8.2, while the MATLAB toolbox was used for GA. The Pareto optimal solutions are given in Tables 3.8 to 3.11, while graphical representations of these solutions are presented in Figure 3.8 to Figure 3.14. The priority for the preferred optimal solution was based on the highest F_{nadir} , followed by the lowest P_{losses} and then the lowest V_d .

Table 3.9: Possible solutions using DSO

Serial number	BESS Multiplier (λ_{BESS})	Frequency nadir (F_{nadir} (pu))	Voltage deviation (V_d (pu))	Power losses (P_{losses} (pu))
1	0.5000	0.9878	0.0306	0.9812
2	1.5000	0.9890	0.0315	0.9505
3	1.2906	0.9889	0.0315	0.9562
4	0.9837	0.9887	0.0313	0.9652
5	0.5720	0.9880	0.0308	0.9787
6	1.0543	0.9888	0.0313	0.9630
7	1.3603	0.9889	0.0315	0.9542
8	1.3139	0.9889	0.0315	0.9555
9	0.5362	0.9879	0.0307	0.9799
10	1.0105	0.9887	0.0313	0.9644
11	0.5499	0.9879	0.0307	0.9795
12	1.4257	0.9889	0.0315	0.9524
13	1.0331	0.9887	0.0313	0.9637
14	0.6799	0.9882	0.0309	0.9750

15	0.9166	0.9886	0.0312	0.9673
16	1.2486	0.9889	0.0314	0.9573
17	1.3953	0.9889	0.0315	0.9533
18	1.1607	0.9888	0.0314	0.9599
19	1.0915	0.9888	0.0314	0.9619
20	0.9420	0.9886	0.0313	0.9665
21	0.5205	0.9879	0.0307	0.9805
22	0.8891	0.9886	0.0312	0.9682
23	0.9550	0.9887	0.0313	0.9661
24	0.7864	0.9884	0.0311	0.9715
25	0.9711	0.9887	0.0313	0.9656
26	0.6161	0.9881	0.0308	0.9772
27	0.6329	0.9881	0.0309	0.9766
28	1.1817	0.9888	0.0314	0.9593
29	0.6665	0.9882	0.0309	0.9755
30	0.6551	0.9882	0.0309	0.9758
31	1.1386	0.9888	0.0314	0.9605
32	0.8360	0.9885	0.0311	0.9699
33	1.5021	0.9890	0.0305	0.9508
34	0.7353	0.9883	0.0310	0.9732
35	0.9054	0.9886	0.0312	0.9676
36	0.7651	0.9884	0.0311	0.9722
37	1.3333	0.9889	0.0315	0.9550
38	0.5948	0.9880	0.0308	0.9779
39	0.8185	0.9885	0.0311	0.9704
40	1.1193	0.9888	0.0314	0.9611
41	0.6340	0.9881	0.0309	0.9766
42	0.8014	0.9884	0.0311	0.9710
43	0.5011	0.9848	0.0316	0.9812
44	0.7825	0.9884	0.0311	0.9716
45	1.2156	0.9889	0.0314	0.9583
46	0.7175	0.9883	0.0310	0.9737
47	1.4521	0.9889	0.0315	0.9517
48	1.3599	0.9889	0.0310	0.9542
49	0.5655	0.9880	0.0307	0.9789
50	0.8665	0.9885	0.0312	0.9689

Table 3.10: Best possible solutions (based on priority) using DSO.

Serial number	BESS Multiplier (λ_{BESS})	Frequency nadir (Fnadir (pu))	Voltage deviation (Vd (pu))	Power losses (Plosses (pu))
2	1.5000	0.9890	0.0315	0.9505
8	1.3139	0.9889	0.0315	0.9555
3	1.2906	0.9889	0.0315	0.9562
16	1.2486	0.9889	0.0314	0.9573
45	1.2156	0.9889	0.0314	0.9583

The prioritized best result (highest Fnadir, lowest Plosses and lowest Vd) using DSO:

Optimal BESS Multiplier (λ_{BESS}) = 1.50

From equation (3.34),

BESS optimal size = (Optimal BESS multiplier, ($\lambda_{BESSopt}$)) $\times$ ($BESS_{initial}$)

BESS optimal size = $1.5 \times 96.68 = 145$ MW.

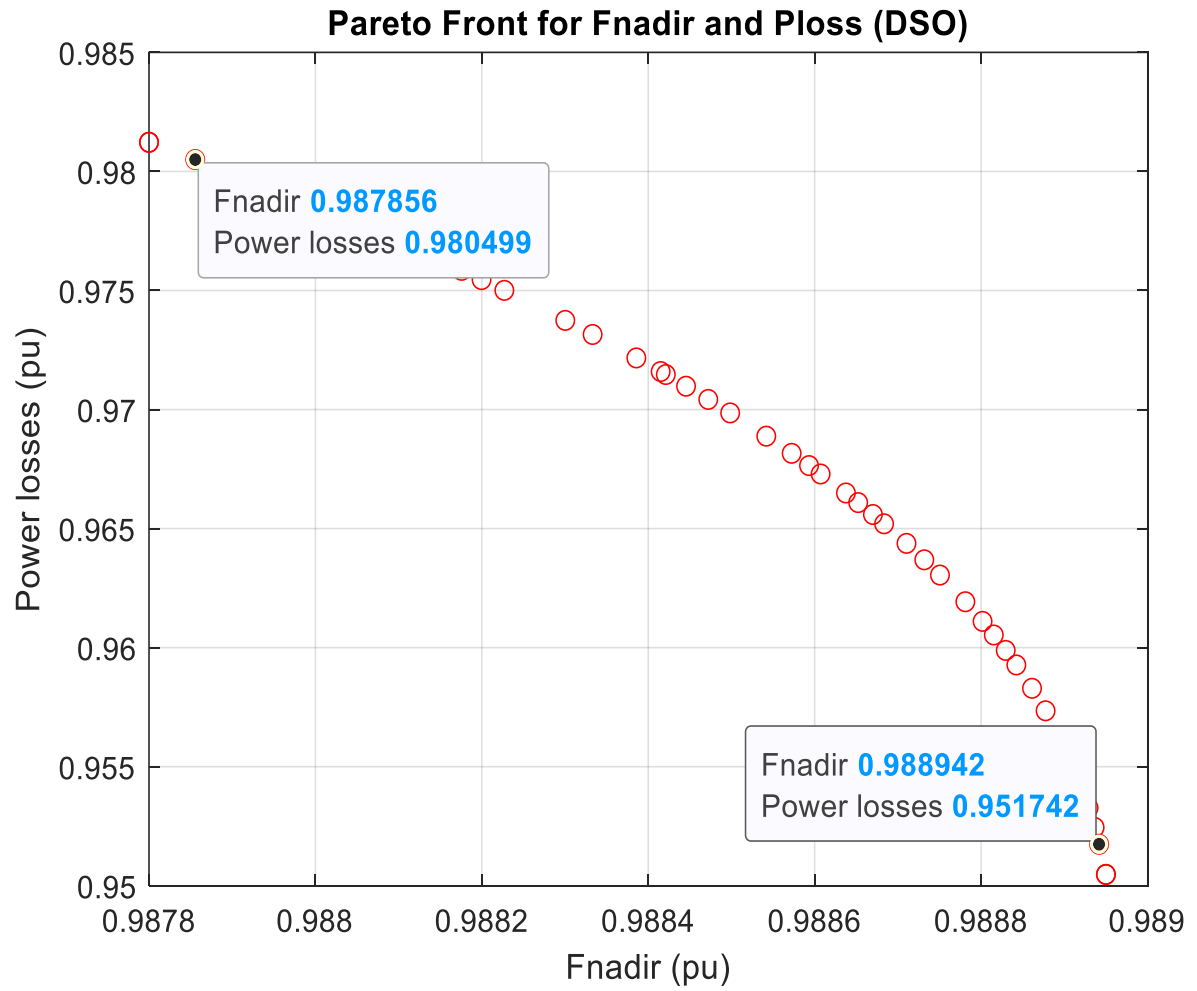


Figure 3.8: The relationship between Plosses and Fnadir determined using DSO

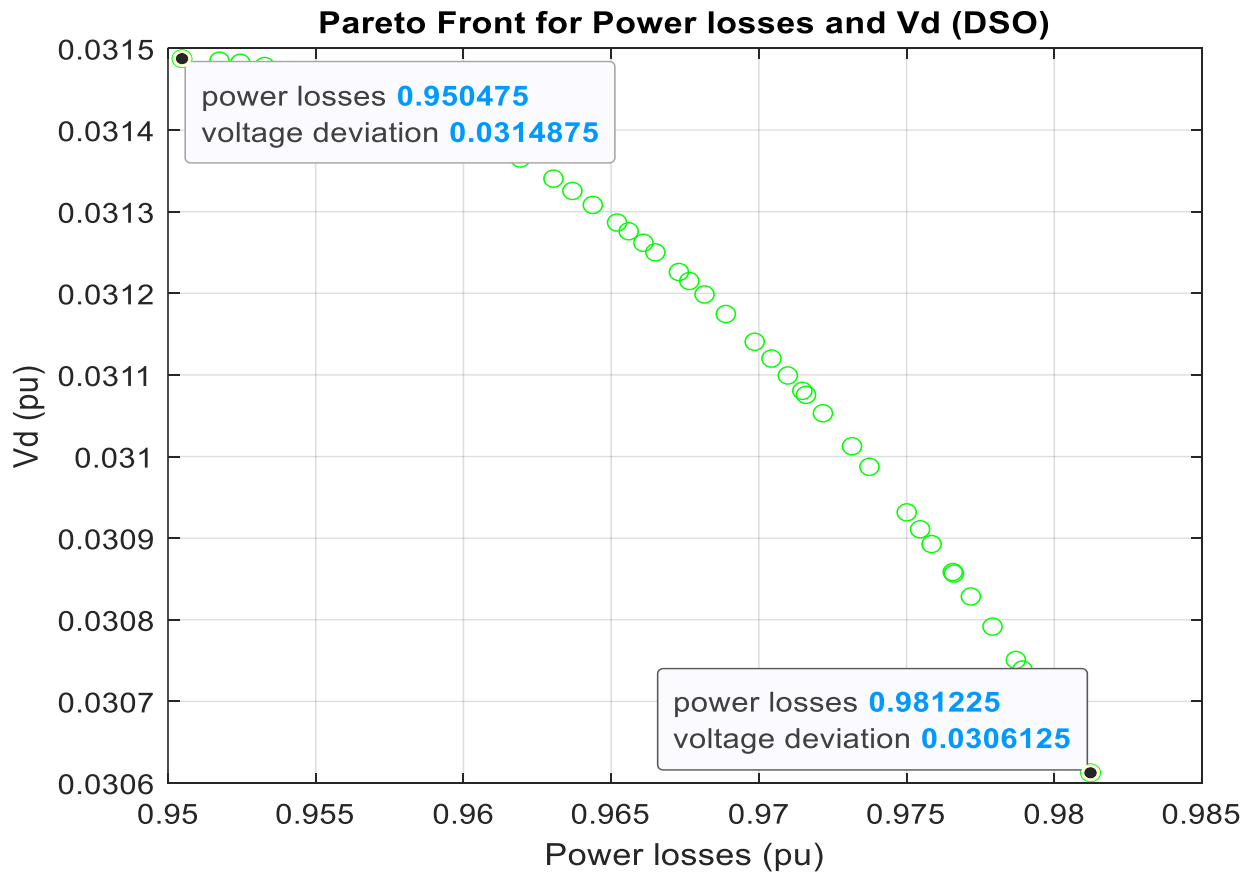


Figure 3.9: The relationship between Plosses and Vd determined using DSO

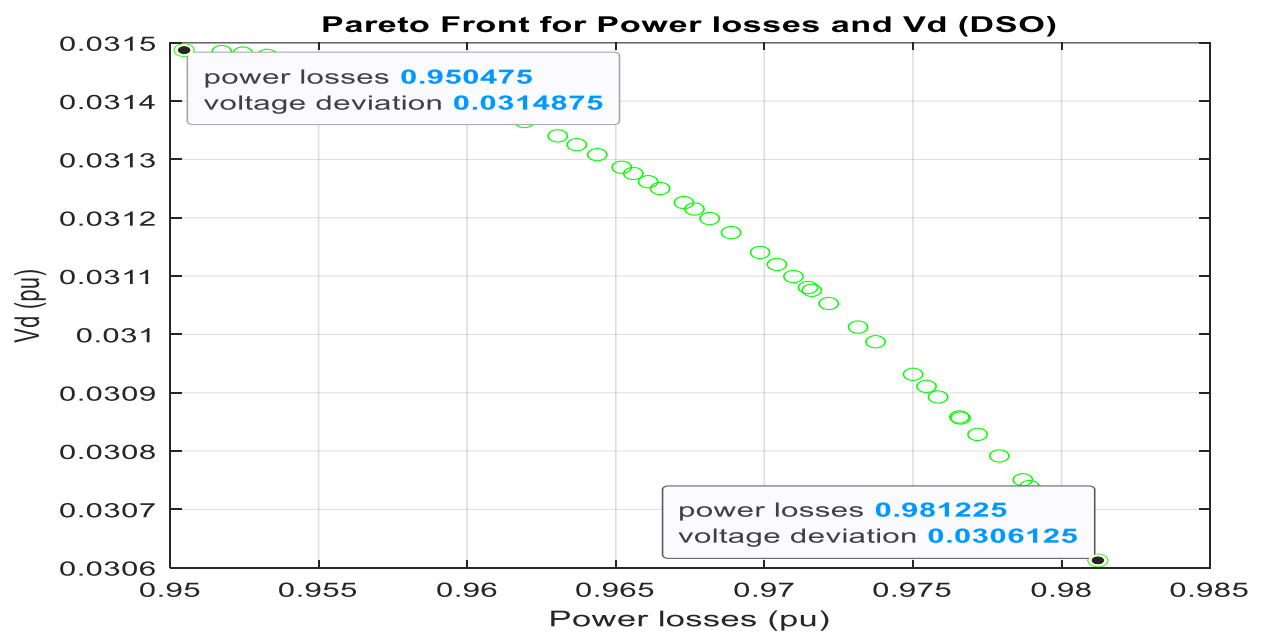


Figure 3.10: The relationship between Vd and Plosses determined using DSO

Table 3.11: Possible solutions from GA

Serial number	BESS Multiplier (λ_{BESS})	Frequency (nadir Fnadir (pu))	Voltage deviation (Vd, (pu))	Power losses (Plosses) (pu)
1	0.5921	0.9878	0.0306	0.9812
2	1.5000	0.9890	0.0315	0.9505
3	0.5880	0.9880	0.0315	0.9781
4	0.7757	0.9884	0.0313	0.9718
5	0.5116	0.9878	0.0308	0.9808
6	1.0434	0.9887	0.0313	0.9634
7	0.8019	0.9884	0.0315	0.9710
8	1.0999	0.9888	0.0315	0.9617
9	1.3839	0.9889	0.0307	0.9536
10	1.1352	0.9888	0.0313	0.9606
11	1.2561	0.9889	0.0307	0.9571
12	0.6269	0.9881	0.0315	0.9767
13	0.5683	0.9880	0.0313	0.9788
14	1.1978	0.9889	0.0309	0.9588
15	1.4510	0.9889	0.0312	0.9518
16	1.0762	0.9888	0.0314	0.9624
17	0.5000	0.9878	0.0315	0.9812
18	0.6812	0.9882	0.0314	0.9750
19	0.7504	0.9884	0.0314	0.9727
20	1.3462	0.9889	0.0313	0.9546
21	0.5366	0.9879	0.0307	0.9799
22	0.6488	0.9882	0.0312	0.9761
23	1.3348	0.9889	0.0313	0.9549
24	0.6666	0.9882	0.0311	0.9755
25	1.3785	0.9889	0.0313	0.9537
26	0.9486	0.9886	0.0308	0.9663
27	0.8983	0.9886	0.0309	0.9679
28	0.7084	0.9883	0.0314	0.9740
29	0.6038	0.9881	0.0309	0.9776
30	1.500	0.9889	0.0309	0.9505
31	1.008	0.9887	0.0314	0.9647
32	1.3032	0.9889	0.0311	0.9558
33	1.4276	0.9889	0.0315	0.9524
34	1.5000	0.9890	0.0310	0.9505
35	0.5509	0.9879	0.0312	0.9794
36	1.2635	0.9889	0.0311	0.9569
37	0.9969	0.9887	0.0315	0.9648

38	0.9423	0.9886	0.0308	0.9665
39	1.2227	0.9889	0.0311	0.9581
40	1.4091	0.9889	0.0314	0.9529
41	1.2204	0.9889	0.0309	0.9582
42	1.1804	0.9888	0.0311	0.9593
43	0.5924	0.9880	0.0306	0.9780
44	0.6268	0.9881	0.0311	0.9768
45	0.8669	0.9885	0.0314	0.9689
46	1.2846	0.9889	0.0310	0.9563
47	0.8512	0.9885	0.0315	0.9694
48	0.9161	0.9886	0.0315	0.9673
49	0.7313	0.9883	0.0307	0.9733
50	0.9697	0.9887	0.0312	0.9659

Table 3.12: Best possible solutions (based on priority) using GA

Serial number	BESS Multiplier (λ_{BESS})	Frequency nadir (Fnadir (pu))	Voltage deviation (Vd (pu))	Power losses (Plosses (pu))
2	1.5000	0.9890	0.0315	0.9505
14	1.1975	0.9889	0.0309	0.9588
25	1.3785	0.9889	0.0313	0.9537
32	1.3032	0.9889	0.0311	0.9558
36	1.2635	0.9889	0.0311	0.9569

The prioritized best results (highest Fnadir, lowest Plosses, and lowest Vd) using DSO results.

Optimal BESS Multiplier (λ_{BESS}) = 1.50

From equation (3.34),

Optimal BESS size = (Optimal BESS multiplier) $\times$ ($BESS_{initial}$) = (1.50) $\times$ (96.68)

Optimal BESS Size 1.5 $\times$ 96.68 = 145 MW.

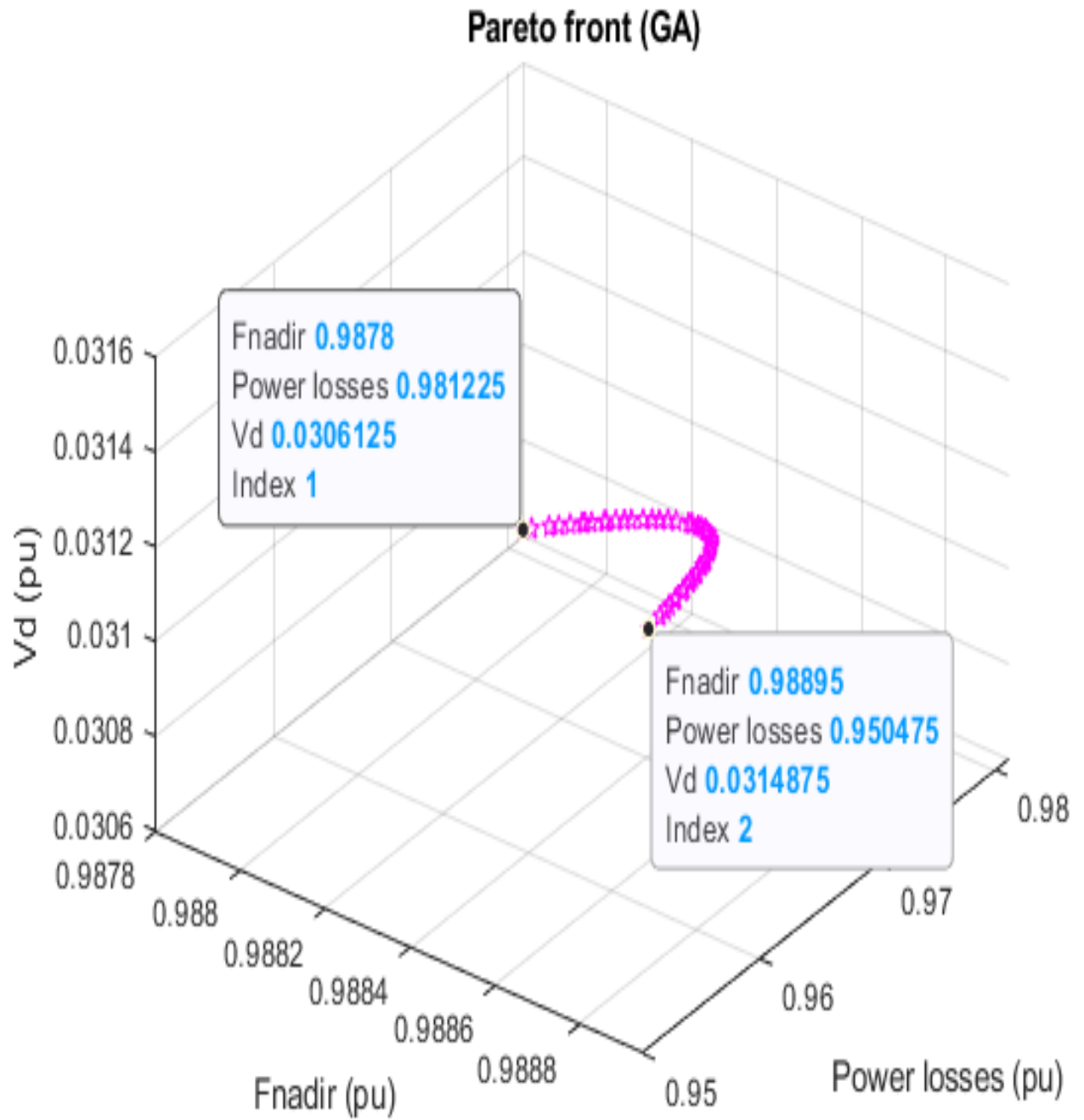


Figure 3.11: The relationships among Fnadir, Plosses, and Vd determined using GA

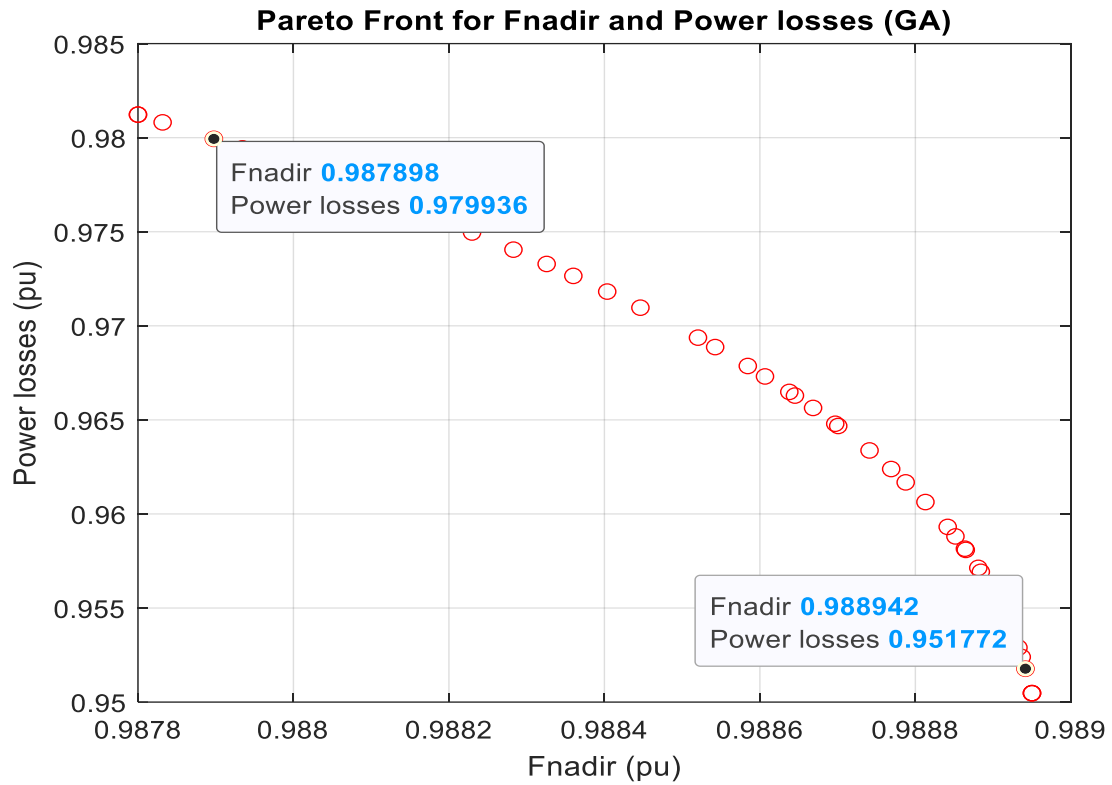


Figure 3.12: The relationship between Fnadir, and Plosses determined using GA

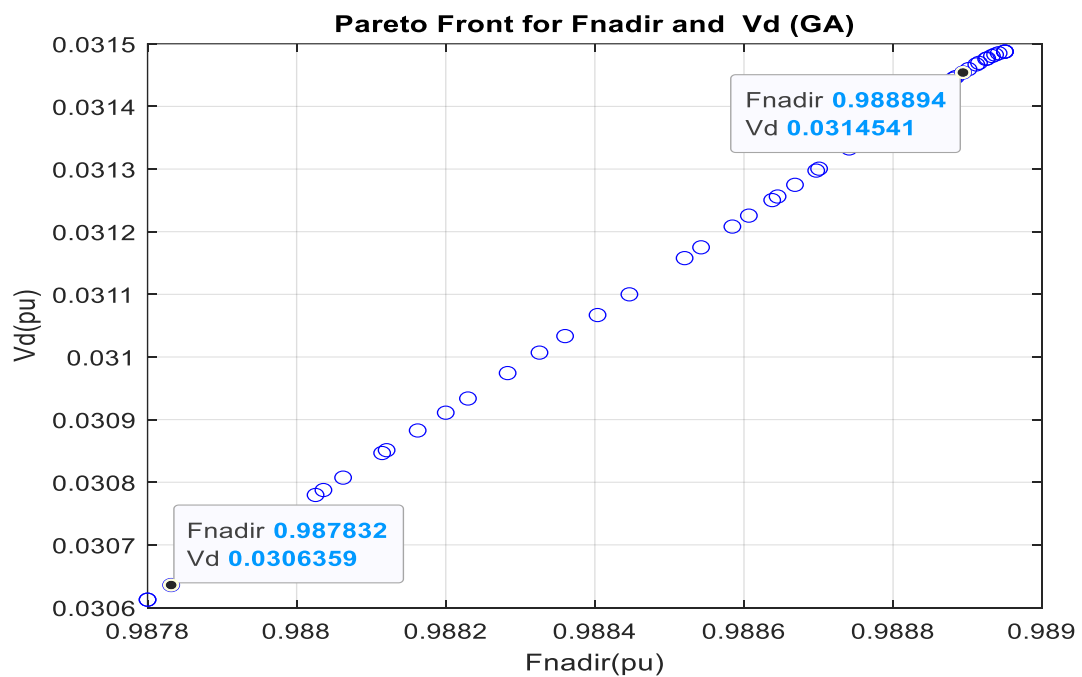


Figure 3.13: The relationship between Fnadir and Vd determined using GA

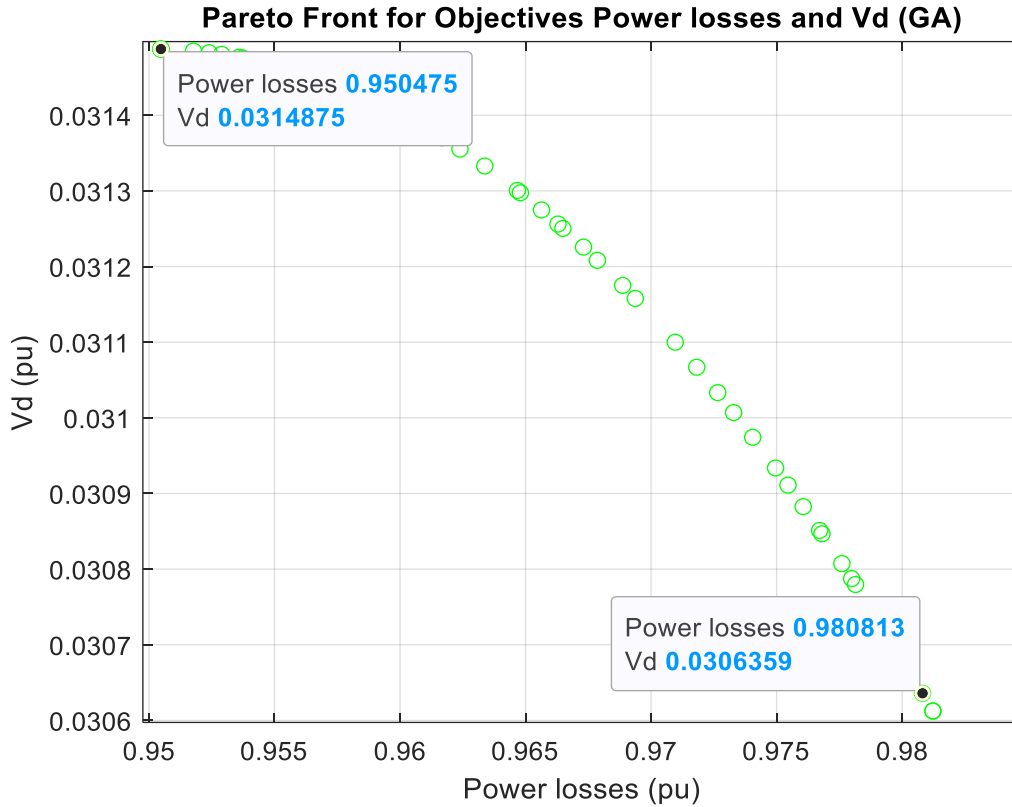


Figure 3.14: The relationship between Vd and Plosses determined using GA

Comparing the results from both the DSO and GA, the optimal size of a BESS (based on the adopted priority) for frequency nadir support during contingency events, reduction of real power losses, and mitigation of voltage deviations for the test system was 145 MW.

3.6.4 Utilizing the optimally sized BESS to support nadir during contingency

A demonstration of the capability of an optimally sized BESS for providing frequency nadir support during contingency events is presented in this section. The DIgSILENT BESS model was adopted with modifications to accommodate the optimal size of 145 MW. This was then connected to bus 39 (i.e., the previously determined optimal location) of the test system. A contingency was initiated at 5 s for an 8 s simulation using the DIgSILENT Power Factory software. Two network conditions were observed:

- A network with no BESS providing frequency nadir support during a contingency event.

- A network with a BESS providing frequency nadir support during a contingency event.

The outcomes of the simulations are provided in Table 3.13 and Figure 3.15.

Table 3.13: Minimum frequencies during a contingency event

Power system network	Frequency nadir (Hz)
Without BESS	59.15
With BESS	59.60

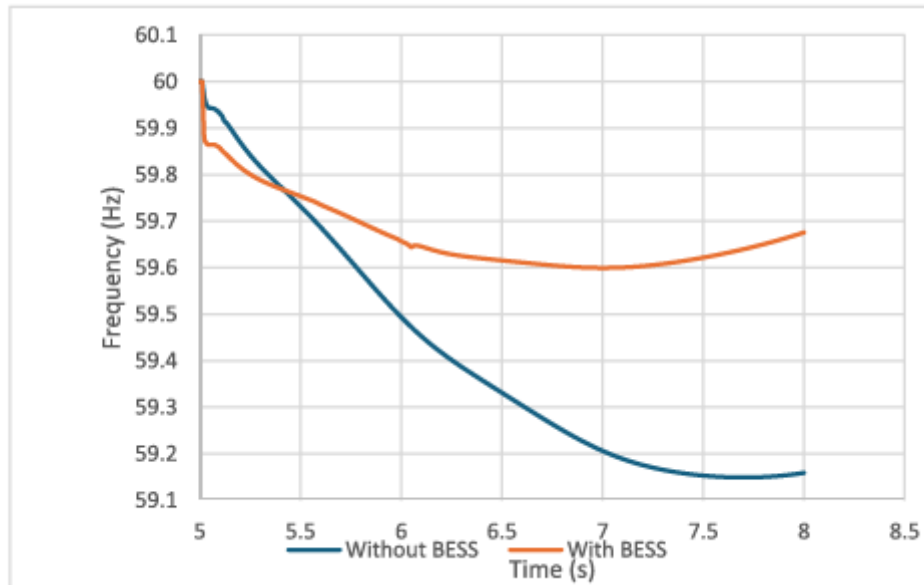


Figure 3.15: Frequency responses using an optimally sized BESS

The capability of the optimally sized BESS (capacity, 145 MW) for providing frequency support during a generator outage contingency was evident from the simulation results. With the support from the BESS, the minimum frequency was sustained at 59.60 Hz during the frequency disturbance event, thereby ensuring frequency stability in the network and a reduced tendency for the activation of underfrequency loadshedding relays.

3.6.5 Mitigating voltage deviations and reducing real power losses using the optimally sized BESS.

To investigate the possibility of reducing voltage deviations using the optimally sized BESS of 145 MW, the voltage in every bus (without a BESS) was studied.

This involved modeling the test system (without a BESS) using the DIgSILENT Power Factory software and conducting a load flow analysis. The results revealed that some of the buses had voltage deviations that were not acceptable according to the grid codes (these are highlighted in red in Table 3.14). Then, an optimally sized BESS was deployed to mitigate the unacceptable voltage deviations. First, a load/voltage analysis of the test system was conducted to ascertain the bus with the most critical voltage condition. This was achieved using the DIgSILENT Power Factory software and the results revealed bus 32 to be the most critical bus. Thereafter, the optimal BESS capacity was connected at bus 32 to supply both real and reactive power to mitigate the unacceptable voltage deviations. Other load flow studies were conducted, and the outcomes are also presented in Table 3.14, while Figure 3.16 presents a graphical comparison of the voltage profiles of the affected buses prior to and after BESS installation.

Table 3.14: Summary of the bus voltages in networks with and without BESS

Bus number	Bus voltage in pu (Network without a BESS)	Bus voltage in pu (Network with a BESS)
1	1.019	1.025
2	1.012	1.025
3	0.980	1.002
4	0.944	0.980
5	0.951	0.986
6	0.953	0.989
7	0.945	0.979
8	0.945	0.978
9	1.007	1.020
10	0.941	0.998
11	0.944	0.994
12	0.947	0.998
13	0.943	0.995
14	0.948	0.989
15	0.961	0.987
16	0.984	1.003
17	0.987	1.006
18	0.983	1.004
19	1.014	1.024
20	0.960	0.967
21	0.998	1.012
22	1.028	1.037

23	1.015	1.026
24	0.993	1.011
25	1.020	1.032
26	1.020	1.033
27	0.999	1.015
28	1.036	1.043
29	1.041	1.046
30	1.048	1.048
31	0.982	0.982
32	0.859	0.970
33	0.997	0.997
34	1.012	1.012
35	1.049	1.049
36	1.015	1.026
37	0.985	0.999
38	1.026	1.026
39	1.030	1.030

From Table 3.14, it is evident that by deploying the 145 MW BESS, the voltage deviations were mitigated, resulting in an acceptable voltage level for all buses in the test system. Additionally, the real power losses decreased from 65.3 to 59.68 MW.

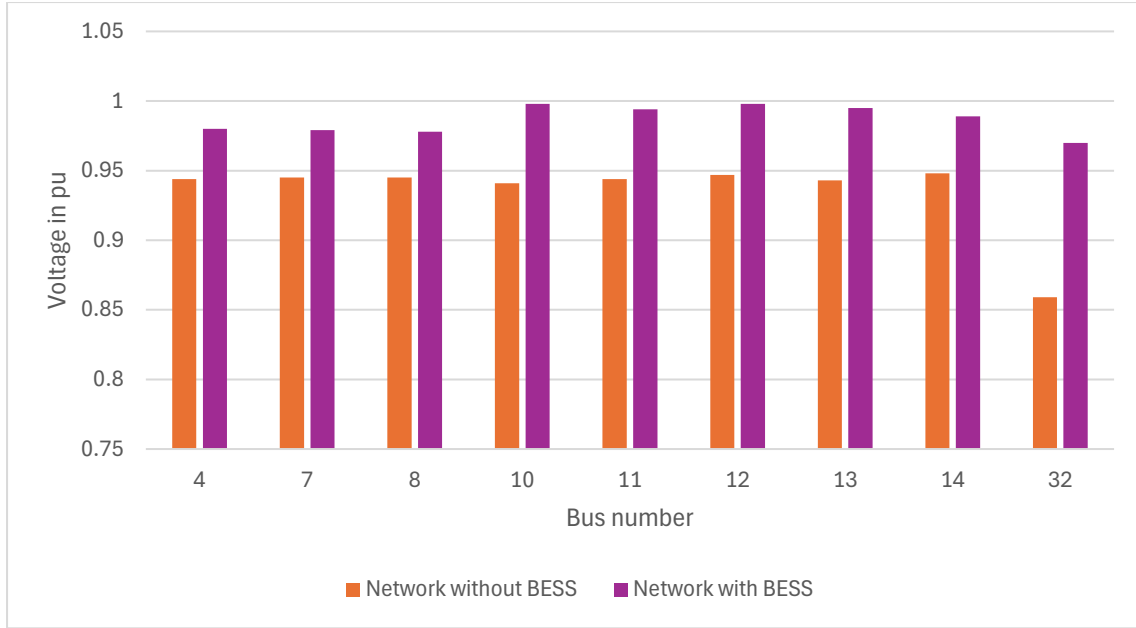


Figure 3.16: Graphical correlation of the voltage profiles of affected buses (with and without a BESS)

3.7 Summary

The strategy for identifying the optimal capacity for a BESS required for multiple applications in a grid with a high renewable energy penetration was presented and discussed. The proposed strategy utilized the concept of a regression analysis to develop mathematical formulations (objective functions) for the determination of the optimal BESS size for multiple functions. The multi-objective functions were then solved using a new metaheuristic algorithm: the DSO algorithm. The results were then validated using the GA, which is a traditional metaheuristic algorithm.

Besides, the BESS optimal capacity determined was deployed for frequency support (during a contingency event), minimization of power losses and mitigation of voltage deviations in an IEEE 39-bus test network. The simulation results presented demonstrated the robustness of the proposed approach.

4. CONTROL OF A BESS FOR MULTIPLE APPLICATIONS

This section focuses on the design of a BESS control system for multiple applications. It also considers implementation strategies for a BESS multi-purpose control system. The services to be delivered to the grid by a BESS through the control unit were frequency nadir support during contingency events, reduction in real power losses, mitigation of voltage deviations, and the supply of reactive power. The test systems used are a generic 12-bus test system for wind power integration studies and a modified 53-bus Western Cape network. The modifications in the 53-bus Western Cape network were made to accommodate the integrations of wind power plants and BESS.

In real-world power systems, frequency regulation controllers (especially for automatic generation control) are designed with consideration of the communication delay between BESSs and grid controllers. Failure to incorporate this may increase the risk of frequency instability [132]-[133]. However, in the present study, the frequency support from the BESS was a fast response (inertia response) with an RoCoF evaluation time of 50–500 milliseconds from the onset of contingency [23], [65]. Therefore, the communication delay was considered to be negligible.

The control system consisted of four sub-units with specific functions. The battery sub-unit consisted of a lithium-ion battery model with a specific number of cells in parallel and in rows. Through an analysis of the battery sub-units, the parameters of the battery cell were found. The remaining three sub-units were controllers, namely the frequency controller, charge controller, and the active/reactive power controllers. A comprehensive analysis of the sub-units is presented in the subsequent sections.

4.1 Description of the BESS multi-purpose control strategy

A block diagram of the BESS control unit is shown in Figure 4.1 [23]

The control system had four sub-units with three signals, namely voltage (U_{meas}), active power (P_{meas}), and frequency (f_{grid}), received from the measurement units in the network. The frequency controller generated the real power reference (P_{ref}) based on the active power imbalance. The PQ controller was defined in the dq reference frame. The dq reference frame is a mathematical tool that converts a three-phase electrical quantity into parallel axis (d) and perpendicular axis (q)

components. With the power reference (P_{ref}) as the input to the PQ controller, and through a dq transformation, the direct current reference (I_{dref}) and the quadrature reference current (I_{qref}) were generated as outputs of the PQ controller. Through the limiter in the charge controller, I_{dref} and I_{qref} were regulated to $I_{dlimref}$ and $I_{qlimref}$ according to the capacity of the power conditioning unit. Through the interconnections of the signals of all the sub-units and measurement systems, the BESS control unit was able to execute the desired multiple functions. There were dual operational protocols for the suggested control unit. Each of the two modes accomplished specific functions. An appropriate size and position of the BESS were crucial for it to effectively provide the desired multiple functions.

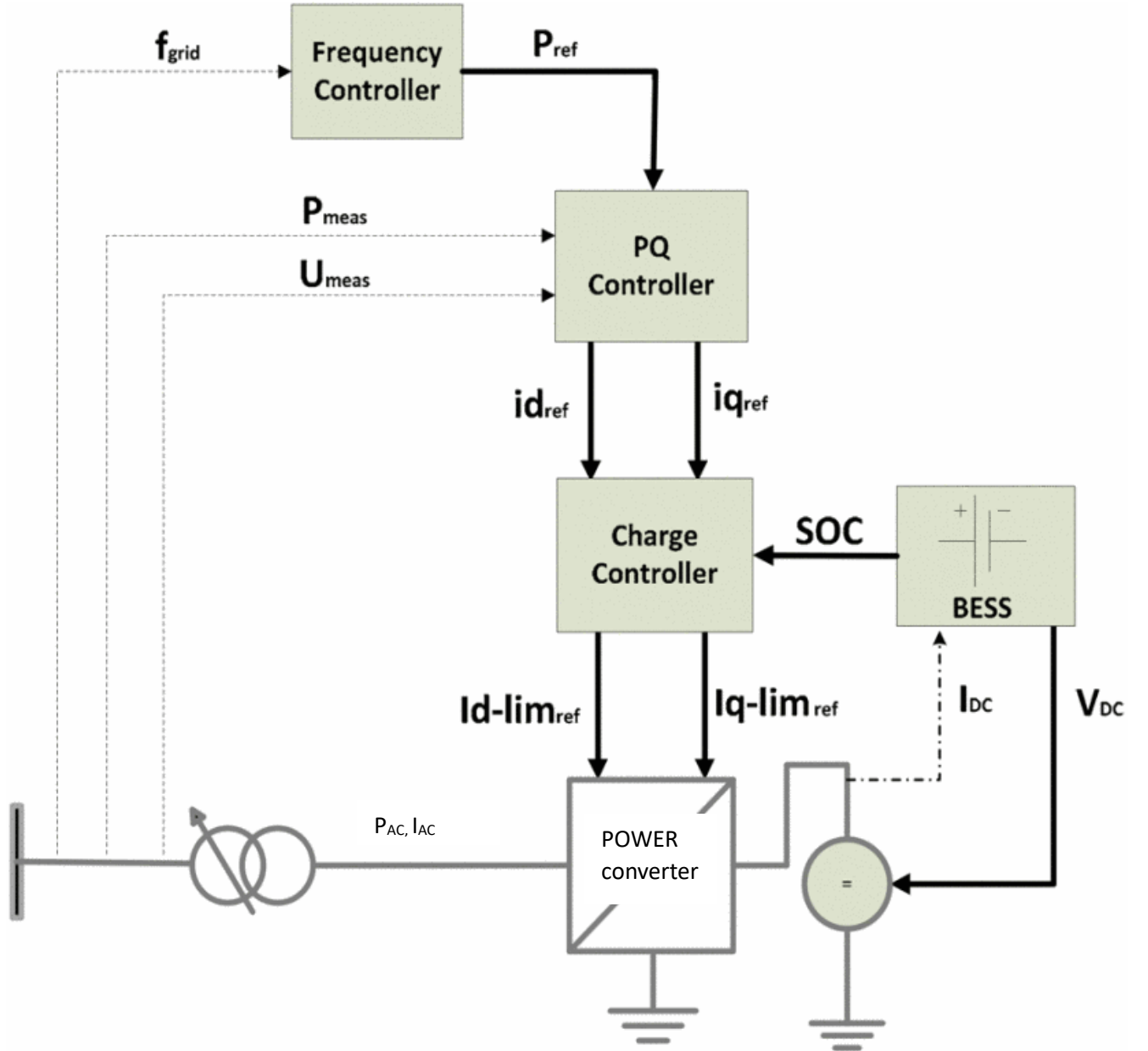


Figure 4.1: Block representation of the BESS control system [23]

Previous studies [35], [36] have shown that the integration of a BESS into a grid network may lead to an increase or decrease in real power losses. Therefore, the optimal size and location is required to maximise the benefits of BESS integration into the grid network. The optimization steps required for determining the optimal size and position of a BESS in a grid network were described in the previous sections of this thesis.

The presence of a significant distortion in the equilibrium between the produced power and load demand in the grid triggers the operation of the BESS to implement frequency support. This contingency event could be an unexpected

rise/decrease in load magnitude or a sudden disconnection of transmission lines. Under such a power system disturbance event, the BESS control system enables it to either inject power to the grid or take power from the grid, depending on the nature of the power system disturbance. The design of each unit of the BESS control system is presented in the following subsections.

4.1.1 The BESS battery unit.

A lithium-ion battery model was used in this study. A schematic and circuit diagrams are shown in Figure 4.2a and Figure 4.2b, respectively.

R_o is the inline resistance

R_{TS} is the partition resistance,

C_{TS} is the partition capacitance,

R_{TL} is the polarization resistance,

C_{TL} is the polarization capacitance,

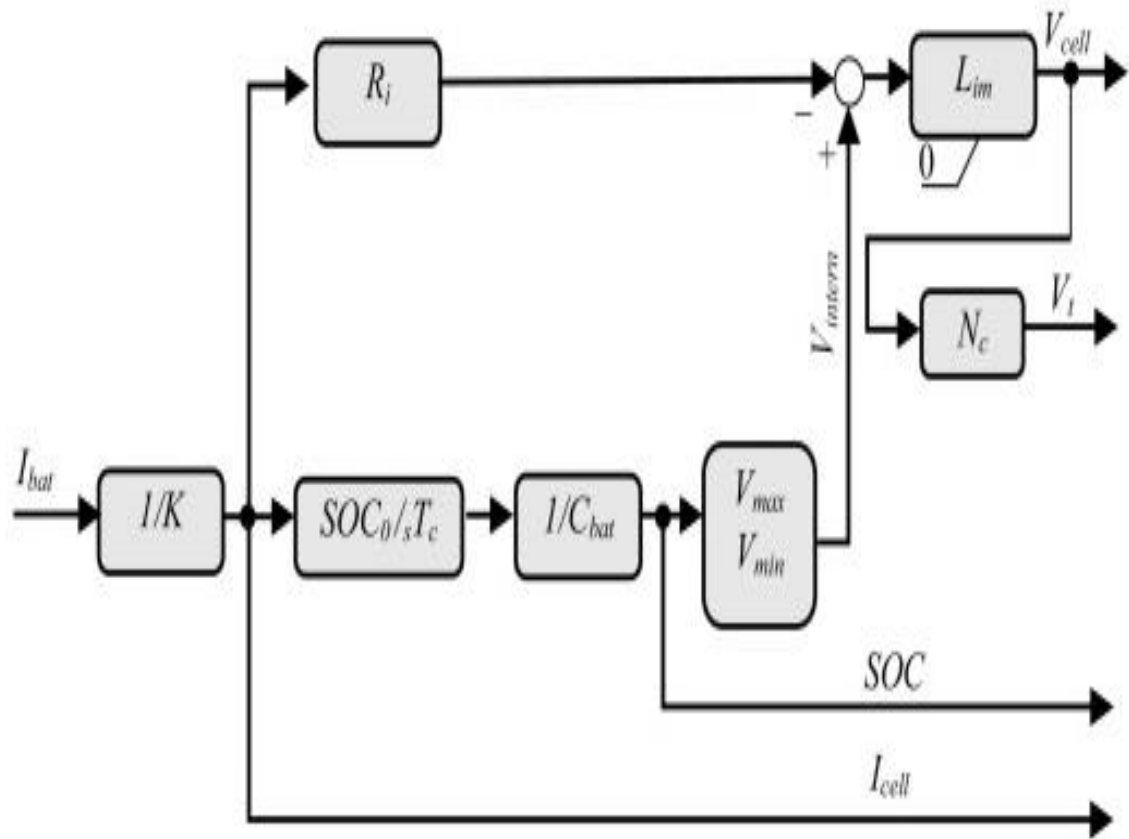
V_{OC} is the no load voltage,

R_{SD} is the leakage resistance.

The battery SOC equation is given below [31]:

$$SOC = SOC_0 - \frac{1}{C_{cell}} \int_0^t I_{cell} dt \quad (4.1)$$

where SOC_0 is the initial SOC; C_{cell} is the size of the cell; and I_{cell} is the current present in one cell. V_{cell} was determined from Figure 4.2b.



(a): Battery model block diagram

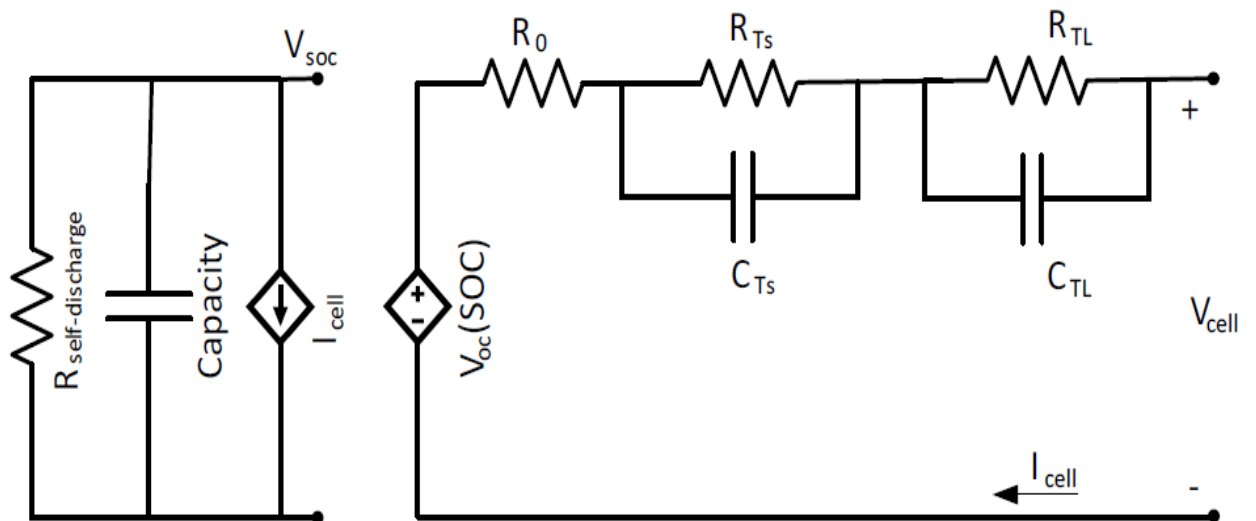


Figure 4.2 (b): Battery cell equivalent circuit.

$$V_{cell} = V_{oc} - I_{cell}R_0 - U_{TS} - U_{TL} \quad (4.2)$$

$$I_{cell} = \frac{U_{TS}}{R_{TS}} + C_{TS} \frac{dU_{TS}}{dt} \quad (4.3)$$

where U_{TS} is the voltage for the polarization process.

Then:

$$\frac{dU_{TS}}{dt} = \frac{I_{cell}}{C_{TS}} - \frac{U_{TS}}{R_{TS}C_{TS}} \quad (4.4)$$

Similarly:

$$I_{cell} = \frac{U_{TL}}{R_{TL}} + C_{TL} \frac{dU_{TL}}{dt} \quad (4.5)$$

$$\frac{dU_{TL}}{dt} = \frac{I_{cell}}{C_{TL}} - \frac{U_{TL}}{R_{TL}C_{TL}} \quad (4.6)$$

where U_{TL} is the voltage due to charge transfer.

The cell array size (n_s) was calculated from equation (4.7):

$$n_s = \frac{U_{batt}}{U_{cell}} \quad (4.7)$$

where U_{batt} is the battery voltage.

Assuming the load demand from the battery (P_{batt}) is known, then the battery rated current (I_{batt}) could be determined as follows:

$$I_{batt} = \frac{P_{batt}}{U_{batt}} \quad (4.8)$$

Strings in parallel (n_p), could be deduced from equation (4.9)

$$n_p = \frac{I_{batt}}{I_{cell}} \quad (4.9)$$

where I_{cell} is the amount of current present in one cell.

The values of the parameters, V_{oc} , R_o , C_{TS} , R_{TS} , R_{TL} , and C_{TL} can be approximated from equations (4.10–4.15) according to Chen and Rincón-Mora [134].

$$V_{oc}(\text{SOC}) = -1.031e^{-35\text{SOC}} + 3.685 + 0.2156(\text{SOC}) - 0.1178(\text{SOC})^2 + 0.3201(\text{SOC})^3 \quad (4.10)$$

$$R_o(\text{SOC}) = 0.1562e^{-24.37\text{SOC}} + 0.07446 \quad (4.11)$$

$$R_{TS}(\text{SOC}) = 0.3208.e^{-29.14\text{SOC}} + 0.04669 \quad (4.12)$$

$$C_{TS}(\text{SOC}) = -752.9e^{-13.51\text{SOC}} + 703.6 \quad (4.13)$$

$$R_{TL}(\text{SOC}) = 6.603e^{-155.2\text{SOC}} + 0.04984 \quad (4.14)$$

$$C_{TL}(\text{SOC}) = -6056e^{-27.12\text{SOC}} + 4475 \quad (4.15)$$

A lithium-ion battery cell has an internal resistance that is dependent on the SOC and temperature [134]-[136]. It maintains fairly constant values for all RC parameters between 20% to 80% SoC [134], [136]. In the present study, an internal resistance of 30 mΩ was selected [136].

For a battery with a total charge of Q_{total} (Ah), with n_s being the number of cells in a string; n_p is the number of strings in parallel; and Q_{cell} is the cell size of a battery, then equation (4.16) gives the relationship between the battery parameters.

$$Q_{\text{total}}(\text{Ah}) = n_s \times n_p \times Q_{\text{cell}} \quad (4.16)$$

To obtain the battery parameters, the battery capacity used in Okafor and Folly [19] was adopted given that the same test system and frequency disturbance event were adopted.

Size of BESS = 57 MW.

A battery module of 900V was selected.

I_{batt} from equation (4.8) was 63.333 kA

A '3C' rated cell with a cell size of 80 Ah was adopted.

Then, $I_{\text{cell}} = 240 \text{ A}$.

Using equation (4.9), (n_p) was approximately 264.

The lithium-ion battery had a nominal cell voltage of approximately 3.7 V.

Thus, $n_s = 243$ from equation (4.7).

Taking into account the health of the lithium-ion battery, SOC values between 0.2 and 0.8 were selected. The parameters of the batteries are given in Table 4.1.

Table 4.1: Metrics of the battery model.

Parameter	Value
State of charge at initialization (SoC ₀)	0.8
Cell capacity per cell (Ah)	80
Minimum voltage of cell (V)	12
Maximum voltage of cell (V)	13.8
Number of parallel cells	264
Number of cells in a row	243
Cell internal resistance per cell (ohm)	0.003

4.1.2 The frequency controller model

The decision to inject power into the grid or absorb power from the grid at the moment the generation/load equilibrium is disrupted is undertaken by the frequency controller. Whenever the grid frequency (f_g) is at variance with the normal frequency (f_0), the frequency controller executes fundamental actions in accordance with equation (4.17):

$$df = f_0 - f_g \quad (4.17)$$

where df is the frequency deviation.

If df is positive, the discharging mode of the BESS is activated, and it supplies power to the grid. However, if it is negative, the charging mode is activated and the BESS acts as a load and draws power from the grid.

The frequency controller design considered in this study was droop-based, as shown in the block diagram in Figure 4.3. The total active power absorbed or injected during a contingency event was determined by the droop.

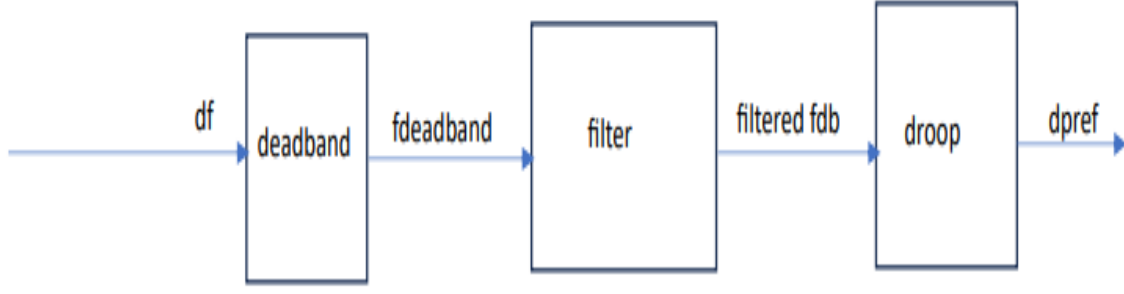


Figure 4.3: A block diagram of the frequency control unit

Using equation (4.18), the frequency droop (K_{droop}) is determined according to Glover et al. [137]:

$$K_{droop} = \frac{\Delta P}{\Delta f} \quad (4.18)$$

where Δf and ΔP are the mismatch in frequency and real power (in pu) respectively:

Using equation (4.19), Δf (pu) is determined according to [137]:

$$\Delta f(\text{pu}) = \frac{f_{ref} - f_{mea}}{f_{ref}} \quad (4.19)$$

The nominal frequency, represented by f_{ref} , is 50 Hz and f_{mea} is the new frequency arising from the power mismatch given as $\Delta P(\text{pu})$, which is determined using equation (4.20) [137]:

$$\Delta P(\text{pu}) = \frac{P_1 - P_2}{S_{base}} \quad (4.20)$$

The active power P_1 is the power released before the contingency event and P_2 is the real power after a power deficit. S_{base} is the system base. The first order low pass filter actively eliminates the noise [138]. The deadband ensures that the BESS does not respond to all frequency deviations. The value of the deadband is evaluated according to equation (4.21) [139]:

$$\text{Deadband (dB)} = \frac{\text{Acceptable frequency deviation}}{\text{system frequency}} \quad (4.21)$$

For an allowable deviation of 0.2 Hz, and a frequency disturbance event, equation (4.21) is used to determine the value of the deadband while equation (4.18) evaluates the frequency droop. The specifications of the frequency controller are given in Table 4.2.

Table 4.2: Metrics of the frequency controller

Description of parameter	Values
Deadband (dB)	0.004
Frequency droop (K_{droop})	0.002

4.1.3 Controller for the real and reactive power (PQ controller)

For the control of the real and the active power, a PQ controller model was used, as shown in Figure 4.4 [23]. Proportional integral controllers regulated the active and reactive power. The first-order filter model (which had a small time constant) filtered out the high-frequency noise [23]. Voltage support was provided by the AC deadband [139]. The required regulation was achieved through use of the dq reference frame.

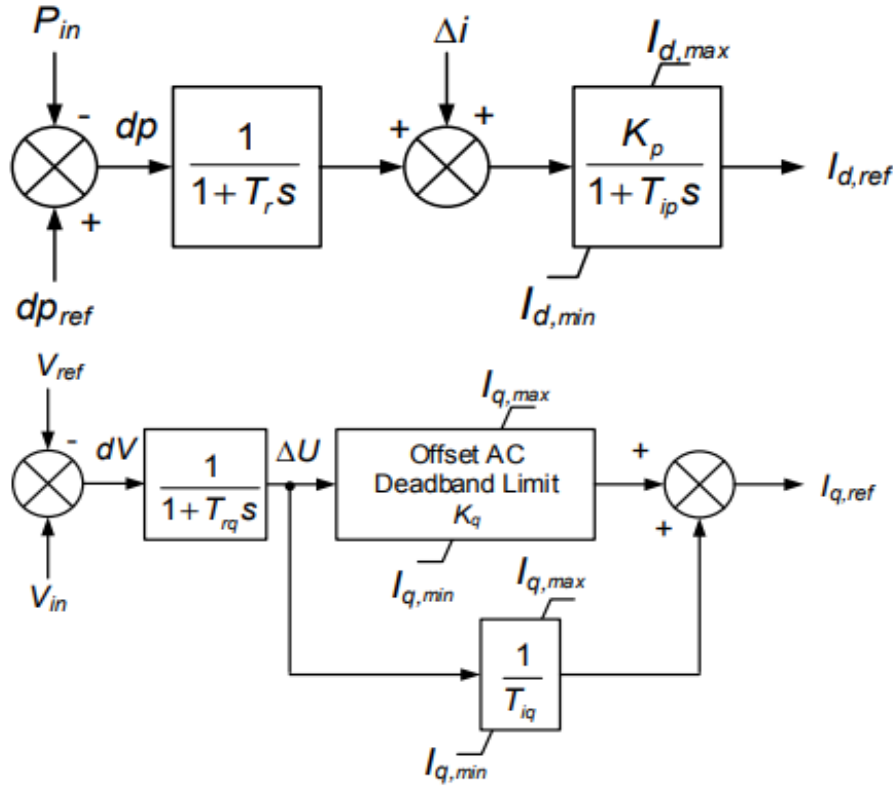


Figure 4.4: The PQ controller model

Through a combination of Clarke and the Park transformations, the electrical quantities were converted from a 3-phase quantity to a dq rotating quantity. The Clarke transformation converted the 3-phase parameters into $(\alpha - \beta)$ values, while the Park formula enabled an additional transformation from the $(\alpha - \beta)$ values into a dq axis component [140], [141] [142]. The mathematical relationships for the change from f_a , f_b , and f_c to $(\alpha - \beta)$ values is given in equation (4.22) [140]-[141].

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (4.22)$$

where f_α and f_β are two $(\alpha - \beta)$ quantities and f_a, f_b , and f_c are 3-phase electrical quantities. The $(\alpha - \beta)$ quantities were converted into the dq reference frame using equation (4.23) [140], [141]:

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} f_d \\ f_q \end{bmatrix} \quad (4.23)$$

where θ_r is the rotor angle. Substituting the matrix expression for the $(\alpha - \beta)$ quantities in equation (4.22) into equation (4.23), provides a new expression for the dq variables given in equation (4.24) [140], [142]:

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r - \frac{4\pi}{3}) \\ -\sin\theta_r & -\sin(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r - \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (4.24)$$

Equation (4.24) exemplifies the transformation process of the three-phase electrical quantities f_a, f_b , and f_c into two components f_d and f_q . The f_d component is taken as the real active component, while the f_q component represents the reactive component.

The transfer function for the filter model shown in Figure 4.4 is provided in equation (4.25) [108]:

$$H(s) = \frac{V_o(s)}{V_{in}(s)} = \frac{1}{Ts + 1} \quad (4.25)$$

where T is the time constant (which is a fraction of a second); s is the complex frequency; V_o is the output voltage; and V_{in} is the sending end voltage.

With $T = RC$ and the complex frequency $s = j\omega$ (ω is the angular frequency), equation (4.25) is further simplified. Considering the absolute values, this results in equation (4.26):

$$\left| \frac{V_o}{V_{in}} \right| = \left| \frac{1}{(j\omega RC + 1)} \right| \quad (4.26)$$

The additional simplification of equation (4.26) produces equation (4.27):

$$\left| \frac{V_o}{V_{in}} \right| = \frac{1}{\sqrt{(1+\omega^2 R^2 C^2)}} \quad (4.27)$$

With $\omega = 2\pi f$ and frequency = 50 Hz, then R and C values are chosen such that the time constant will be very short (in the order of milliseconds).

The assessment of the metrics of the PI controllers was achieved using the PID tuning function in MATLAB. Table 4.3 gives the metrics of the controller

Table 4.3: Metrics of the PQ controller

Description of each parameter	Value
Filter time constant for d-axis (s) , Tr	0.03
Filter time constant for q-axis (s), Trq	0.01
Proportional gain d-axis, kp	2.0
Integrator time constant d-axis (s) Tip	0.2
Deadband for proportional gain, kdB	0.1
Integration time constant q-axis (s) Tiq	1.0
Proportional gain q-axis, kq	1.0
Integrator time constant, (s) q-axis Tq	1.0
Minimum current d-axis Idmin (pu)	-1.0
Minimum current q-axis Iqmin (pu)	-1.0
Maximum current d-axis Idmax (pu)	1.0
Maximum current q-axis Iqmax (pu)	1.0

4.1.4 The controller that enables the BESS charging and discharging states

The controller model that enables BESS to charge and discharge accordingly is presented in Figure 4.5. It consists of two principal sub-units, namely the charge regulator and current limiter. The direct reference currents from the PQ controller ($I_{d,ref.in}$) and the SOC serve as input signals to the charge control block.

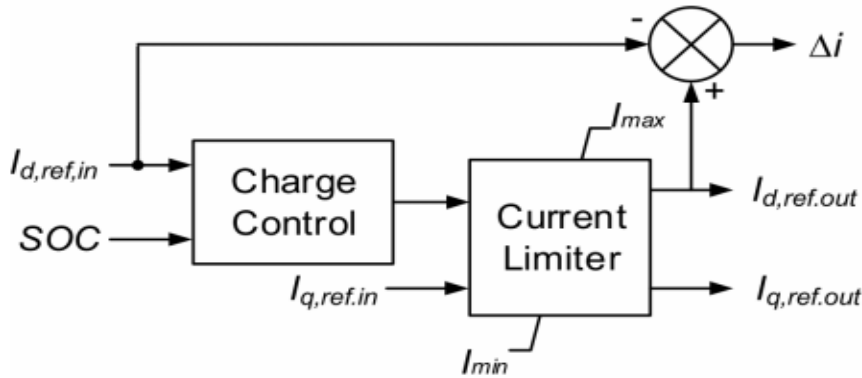


Figure 4.5: Charge and discharge control

The charge regulator houses the charging/discharging algorithms. It also ensures that there is no violation of the SOC condition. The current limiter regulates the $I_{d,ref,out}$ and $I_{q,ref,out}$ such that the converter power limit is not exceeded, as in equation (4.28):

$$S_{PC} = \sqrt{(P_{PC}^2 + Q_{PC}^2)} \quad (4.28)$$

where S_{PC} is the PC's apparent power; and P_{PC} , and Q_{PC} are the real and reactive power, respectively. Equation (4.29) was used to evaluate the current required to charge (I_{charg}) [138], [143]:

$$I_{charg} = \frac{V_{OC} - U_{batt}}{R_O + R_{TS} \left(1 - e^{\frac{-t}{\tau_{TS}}} \right) + R_{TL} \left(1 - e^{\frac{-t}{\tau_{TL}}} \right)} \quad (4.29)$$

where, $\tau_{TS} = R_{TS}C_{TS}$ and $\tau_{TL} = R_{TL}C_{TL}$; τ_{TS} = time constant for the $R_{TS}C_{TS}$ circuit; and τ_{TL} = the time constant for the $R_{TL}C_{TL}$ circuit.

Considering a lithium-ion module battery voltage of $U_{batt} = 900$ V, equations (4.11) to (4.15) could be used to determine τ_{TS} , and τ_{TL} . The charging current (I_{charg}) could be determined from equation (4.29).

Figure 4.6 shows the fixed current and fixed voltage charging method as reported in the literature [138], [144]-[145]. The metrics of the charge/discharge model are given in Table 4.4.

Table 4.4: Metrics of the charge/discharge model

Parameter	Value
Minimum charging current (pu)	0.5
Minimum state if charge (pu)	0.2
Maximum state of charge (pu)	0.8

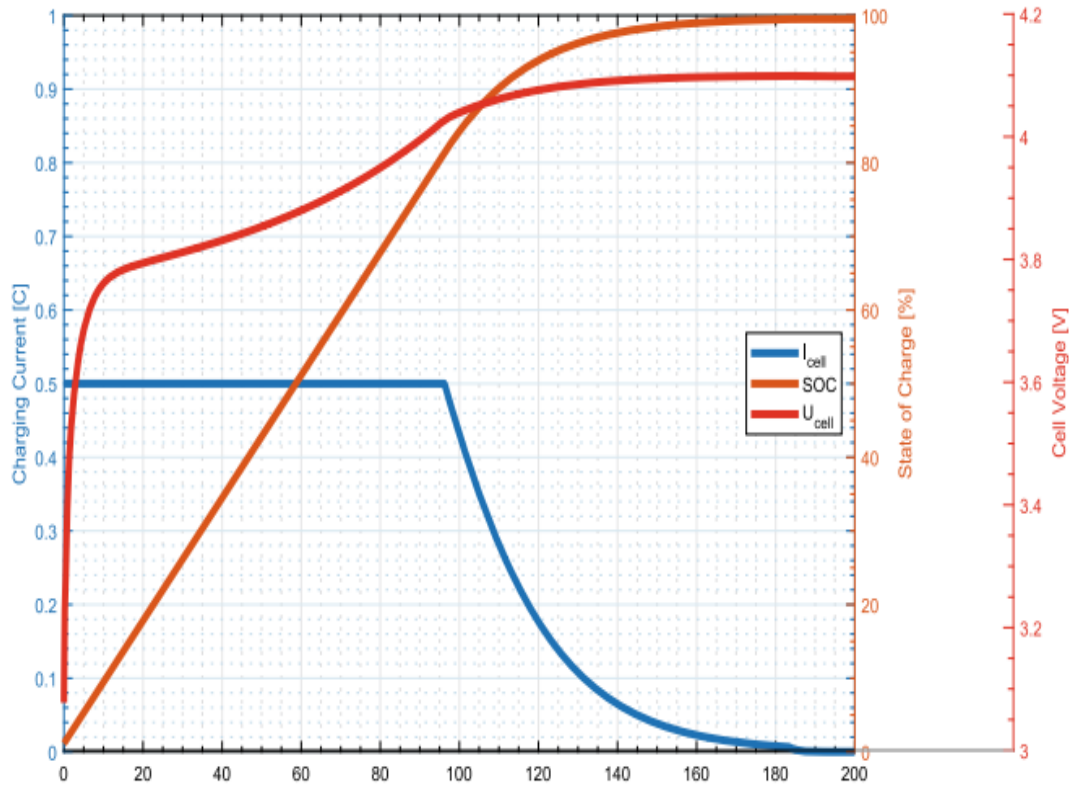


Figure 4.6: Fixed current and fixed voltage method of BESS charging [144]

4.1.5 The PC unit

The PC system changes the voltage signal from the battery into a form acceptable for the basic operations of the grid [27].

4.2 Implementation of the proposed BESS control

4.2.1 Creating block/model definitions.

To implement a control system in DigSILENT, first, block/model definitions were established [38], [146]-[147]. The block diagrams of the control system were used for this purpose. The tasks associated with creating block/model definitions were:

- Accessing all the required standard models (macrons) and assigning them to the appropriate blocks.
- Defining all parameters and variables in the editing page of block/model definitions.
- Defining all mathematical equations (or program codes) in the editing page of mathematical definitions.

Sample screenshots of the standard models and editing pages for model/mathematical definitions are provided in Appendix 8.4.1 to Appendix

8.4.3. Additionally, screenshots of all block/model definitions for the proposed BESS control system are shown in Appendix 8.4.4 to Appendix 8.4.7.

4.2.2 Creation of common models.

The values of the parameters for each of the BESS control sub-units obtained in sub-sections 4.1.1 to 4.1.4 were used to create the common models. The creation of the common models involved assigning known data for the metrics used to create block definitions. Screenshots of all the common models developed for the proposed BESS control sub-units are provided in Appendix 8.4.8 to Appendix 8.4.11.

4.2.3 Creation of composite frames

The composite frames graphically represent the complete control unit. They show the interconnection between the measurement devices and controllers. They were created using slots. Each slot was allocated to a specific controller or element. Every signal in the block/model definitions had to be given the same name in the composite frames; otherwise, the entire control system may not function. The screenshots for the two composite frames for the BESS control sub-units are presented in Appendix 8.4.12 to Appendix 8.4.13.

4.2.4 Creation of the composite model

The composite model connected the power system plant (synchronous generator, wind power plant, battery storage system) with the newly created composite frame [108], [147]. A screenshot of the composite model created for the BESS control system is presented in Appendix 8.4.14.

4.3 Test networks

Two grid networks were deployed to test the validity of the proposed control techniques. A 12-bus test system with a frequency of 50 Hz is according to [148], while a larger system, i.e., the Western Cape network, was previously presented in Figure 2.2. Their generation capacities are summarized in Table 4.5.

Table 4.5: Summary of the test network generation capacities (12-bus)

Power plant	Apparent power (MVA)	Real power (MW)	Number of units
G1	750	525	1

G2	640	250	2
G3	474	300	2
WPP1	250	150	1
WPP2	250	150	1
BESS	57	57	1

4.4 Simulations, results, and discussions

4.4.1 Providing support for the frequency nadir.

In this case, the BESS control provided additional support for the frequency nadir during a 250 MW load rise in the test network. The unexpected rise in the load was initiated 5 s after the 10 s simulation commenced. Table 4.6 shows the values of the lowest frequency attained during the simulation, while Figure 4.7 shows the frequency response.

Table 4.6: Magnitudes of the frequency nadirs (12-bus test network)

Modified 12-bus system	Frequency nadir (Hz)
Without a BESS	48.94
With a BESS	49.04

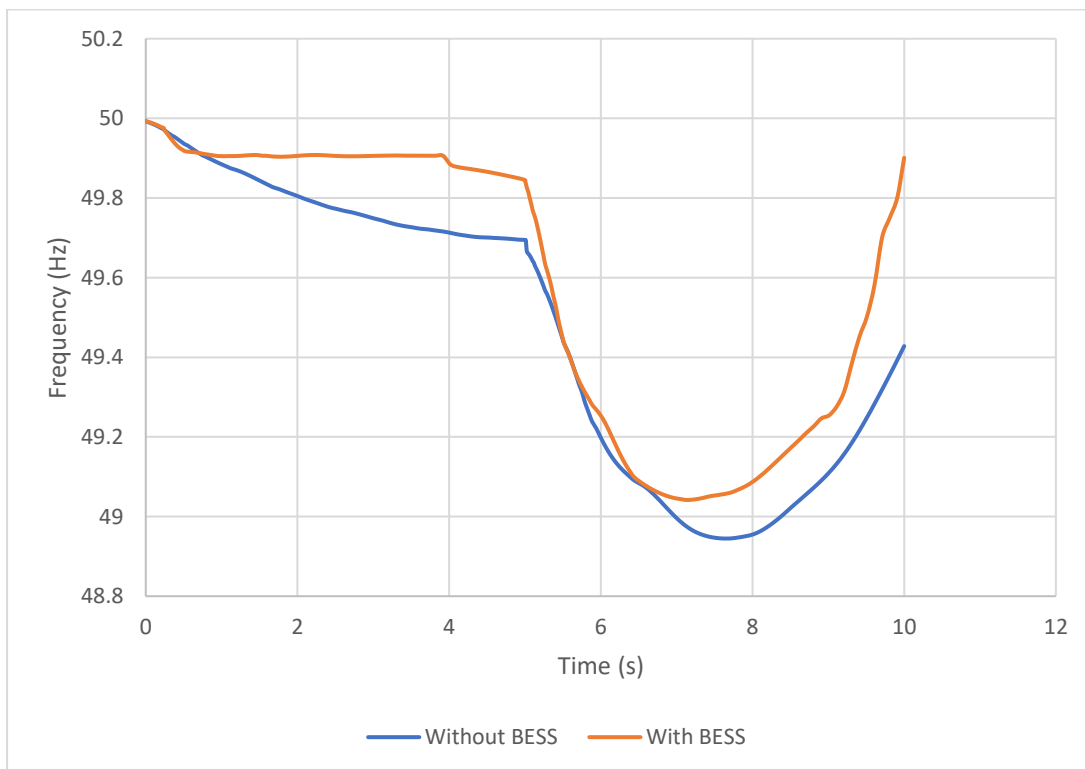


Figure 4.7: Frequency response in the 12-bus test network

Table 4.6 shows the outcome of the simulation, revealing that the BESS was capable of supporting the frequency nadir during the load increase event. It was evident that without the BESS supplying additional frequency nadir support, the frequency nadir (48.94 Hz) may trigger the initialization of sub-nominal frequency relays, resulting in the shedding of some loads.

The magnitude of the real power injected by the inertia supporting energy sources to address the power mismatch due to the real power deficit during the contingency is given in Table 4.7. The corresponding active power injections by these energy sources are shown in Figure 4.8 to Figure 4.10.

Table 4.7: Real power injections (12-bus test network)

Active power sources	Active power injected (MW)
G2	82.8
G3	55.8
BESS	11.1

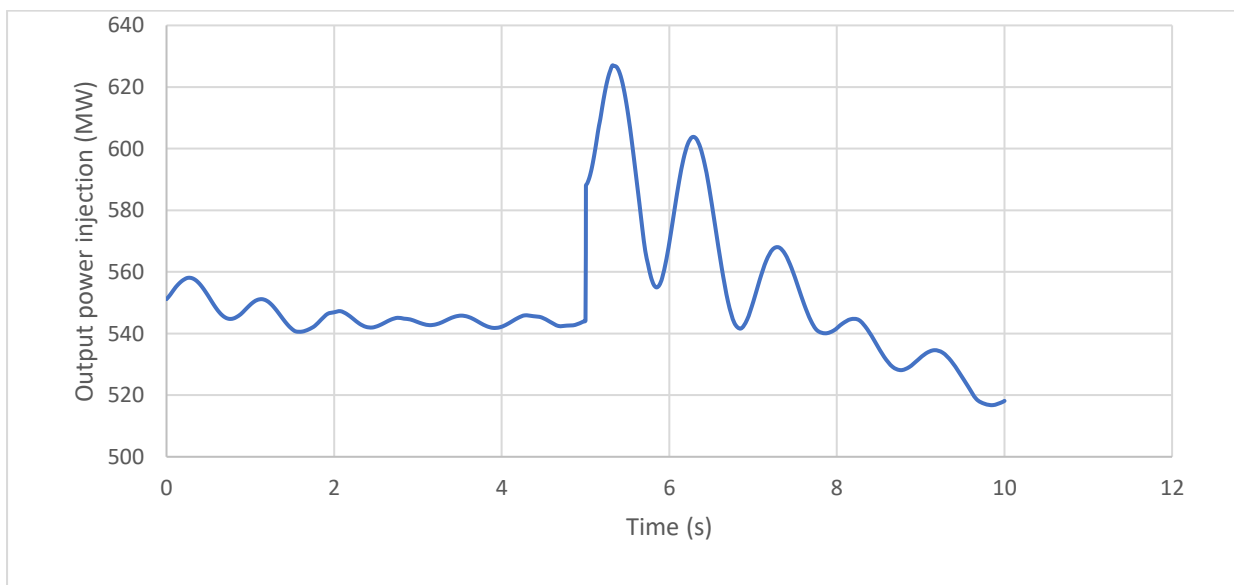


Figure 4.8: The real power injection from the machine at bus 2.

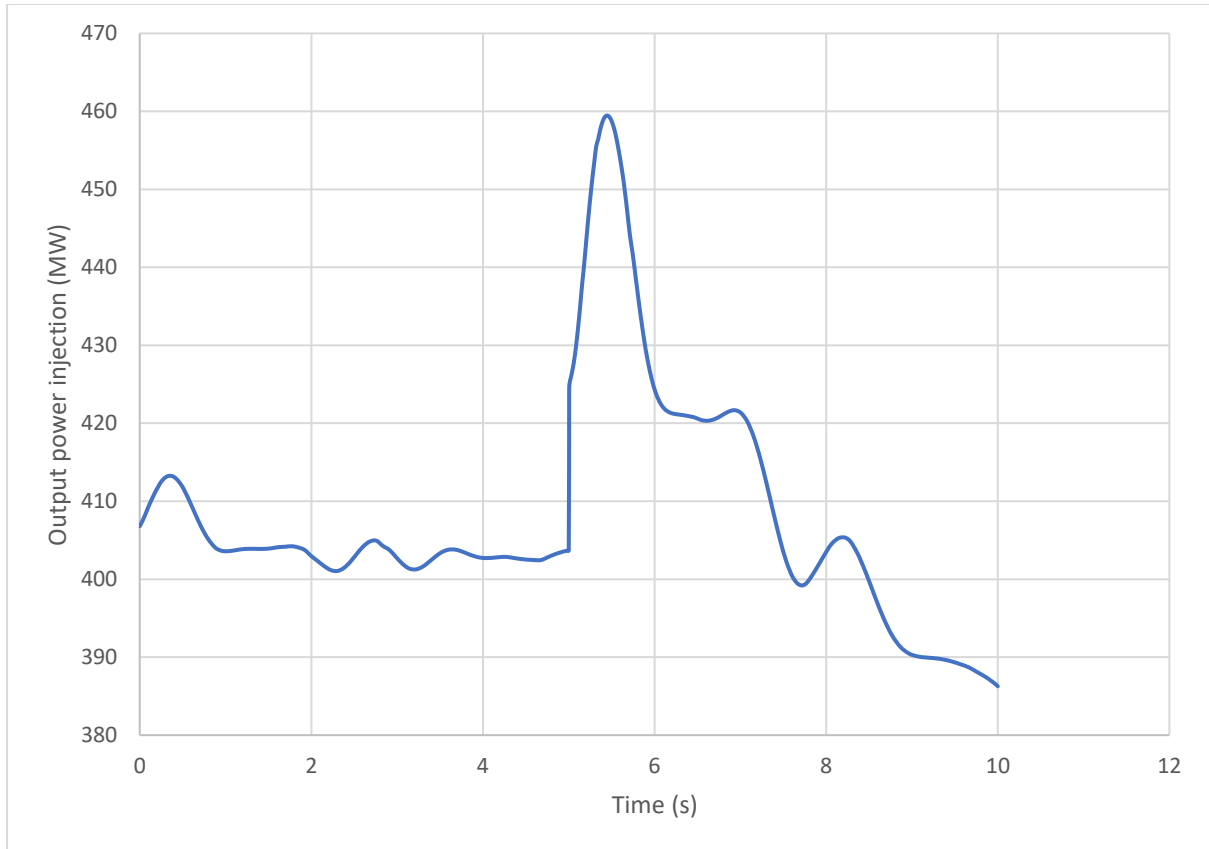


Figure 4.9: The real power injection from the machine at bus 3

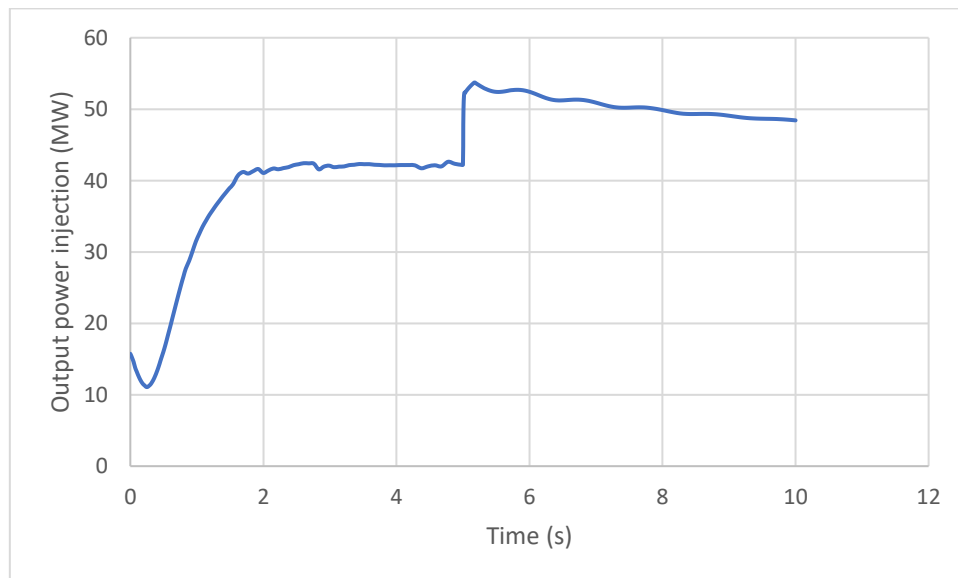


Figure 4.10: The active power injection from the BESS during the load increase contingency.

4.4.2 Frequency nadir support during an unexpected rise in load using the Western Cape network.

The investigation conducted here was comparable to that in section 4.3.1; however, the test system differed. Here, a more practical test system was used, the Western Cape modified 53-bus network. The contingency event initiated was a 350 MW (load increase) for a 10 s simulation, with the sudden increase in load occurring 5 s from the simulation commencing. A summary of the magnitudes of the lowest frequency reached during the contingency event for different network conditions is presented in Table 4.8, while the frequency characteristics are presented in Figure 4.11.

Table 4.8: Magnitudes of the frequency nadirs (Western Cape modified 53-bus network)

Modified 53-bus system	Frequency nadir (Hz)
With a BESS	49.82
Without a BESS	49.74

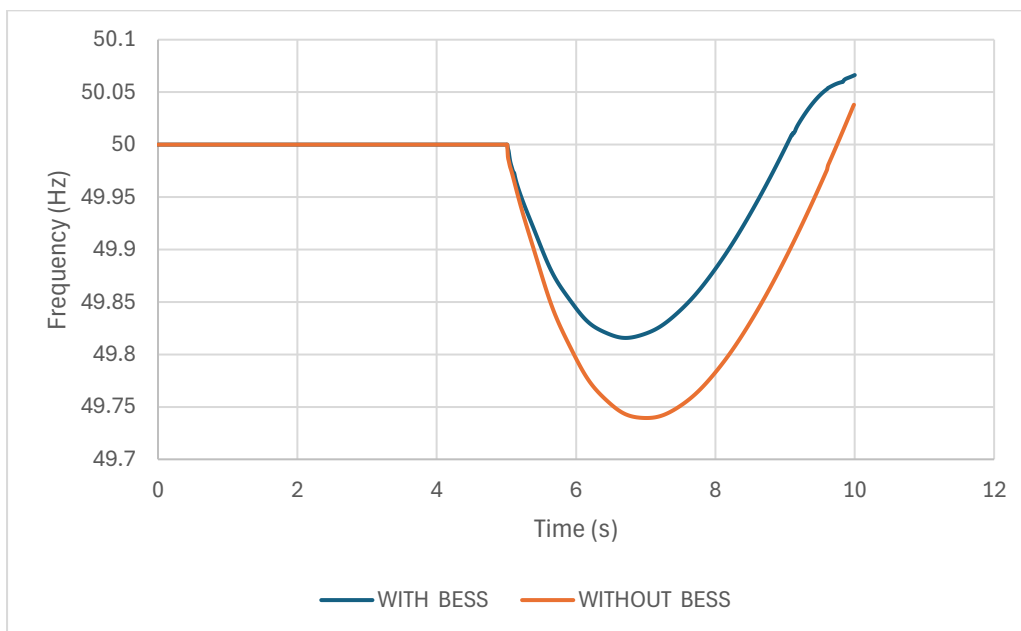


Figure 4.11: Frequency response in the Western Cape modified 53-bus network

The inertia supporting generators also provide support measures in reducing the impact of power mismatches on the network by injecting real power at the

moment of power deficit. Table 4.9 is a summary of the real power compensation supplied.

Table 4.9: Real power injections (Western Cape modified 53-bus network)

Active power sources	Active power injected (MW)
G1	55.9
Ggrid	169.2
BESS	45.4

The real power injections for the three power sources are shown in Figure 4.12 to Figure 4.14. The results in Table 4.9 show that through the use of the proposed techniques, the BESS was able to provide frequency support during the power system frequency event by administering about 45.4 MW of real power to counteract the imbalance between generation and load. With this support from the BESS, the lowest frequency nadir was sustained at 49.82 Hz. However, when eliminating this support, the lowest frequency nadir dropped further to 49.74 Hz. At this frequency, there is a need to engage the release of online generators to ensure that further frequency decay is curtailed. Without such actions, the frequency may fall below the acceptable limit, resulting in a triggering of the underfrequency load shedding relays.

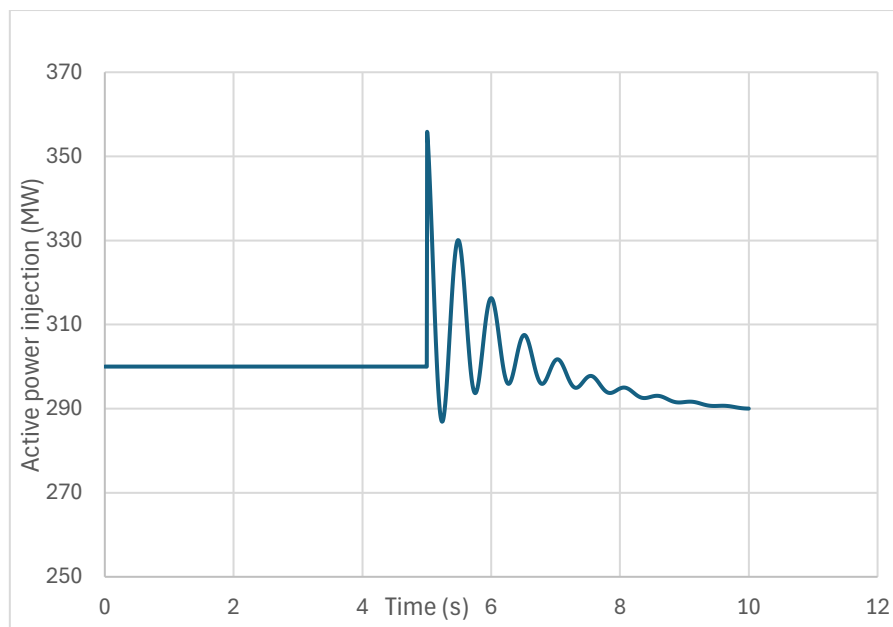


Figure 4.12: Real power injection for G1 (Western Cape modified 53-bus test system)

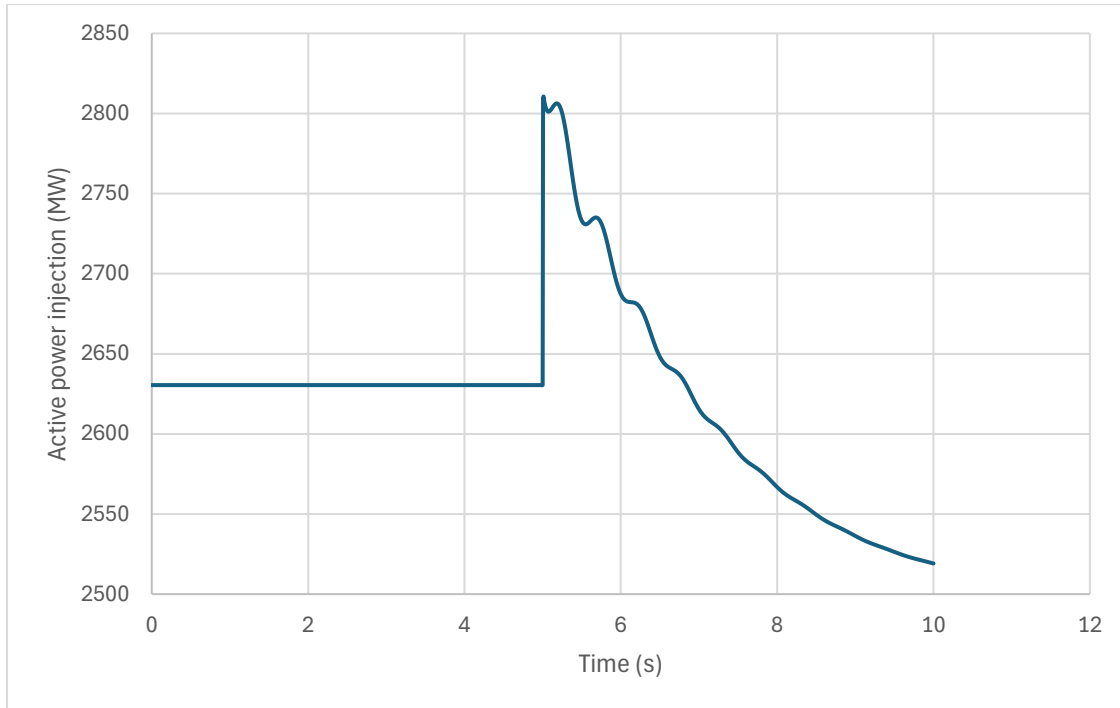


Figure 4.13: Real power injection for the grid (Western Cape modified 53-bus test system)

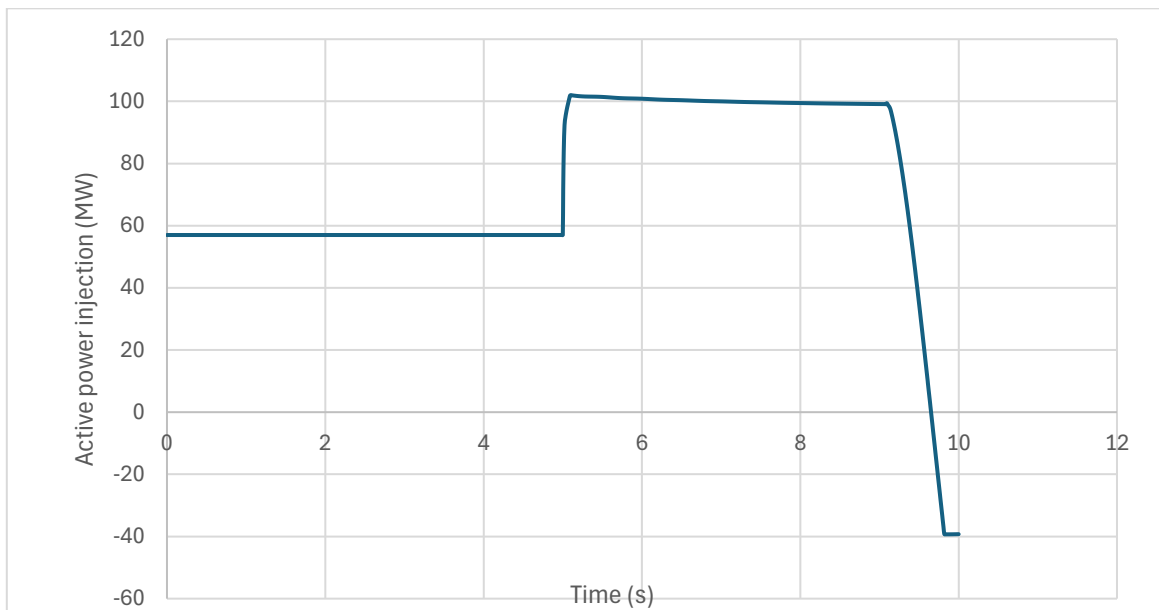


Figure 4.14: Real power injection diagram for the BESS (Western Cape modified 53-bus test system)

4.4.3 Deployment of the proposed control unit with a 12-bus grid network (load decrease event)

This subsection explores the proposed BESS control framework, designed to provide effective support during unexpected load decreases while maintaining the frequency nadir. The maximum frequency reached fell within the permitted frequency threshold because the BESS functions in the charging mode when generation exceeded the load and drew power from the network. Five seconds after the simulation began, a 250 MW drop in the load triggered this scenario in the simulation environment. Figure 4.15 provides a graphic representation of the frequency characteristics while the real power extracted from the network are presented in Figure 4.16 to Figure 4.18. The maximum frequency attainment values at the time of the disturbance are displayed in Table 4.10, while Table 4.11 presents the magnitudes of the real power taken from the network to sustain the frequency at acceptable thresholds.

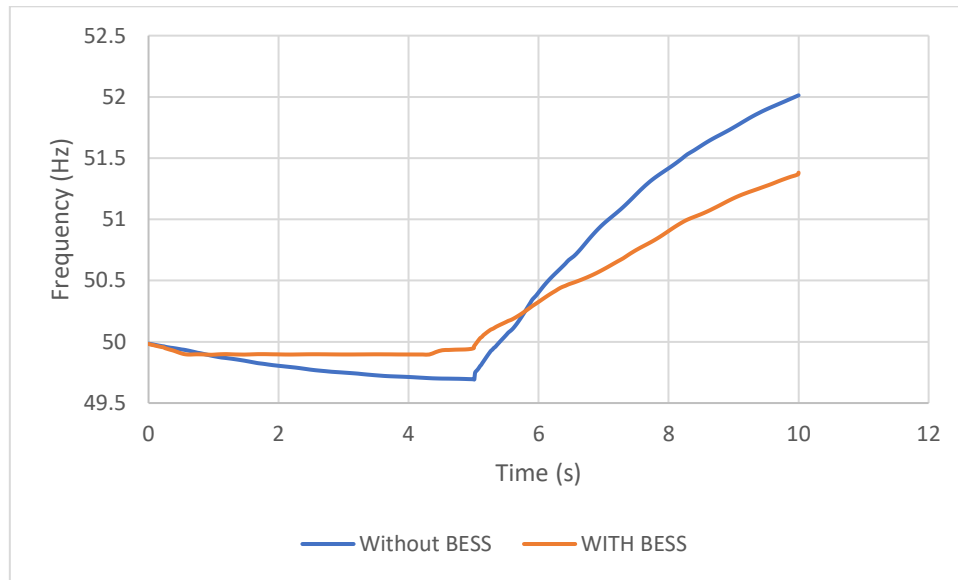


Figure 4.15: Frequency behavior during a 250 MW drop in load (modified 12-bus network)

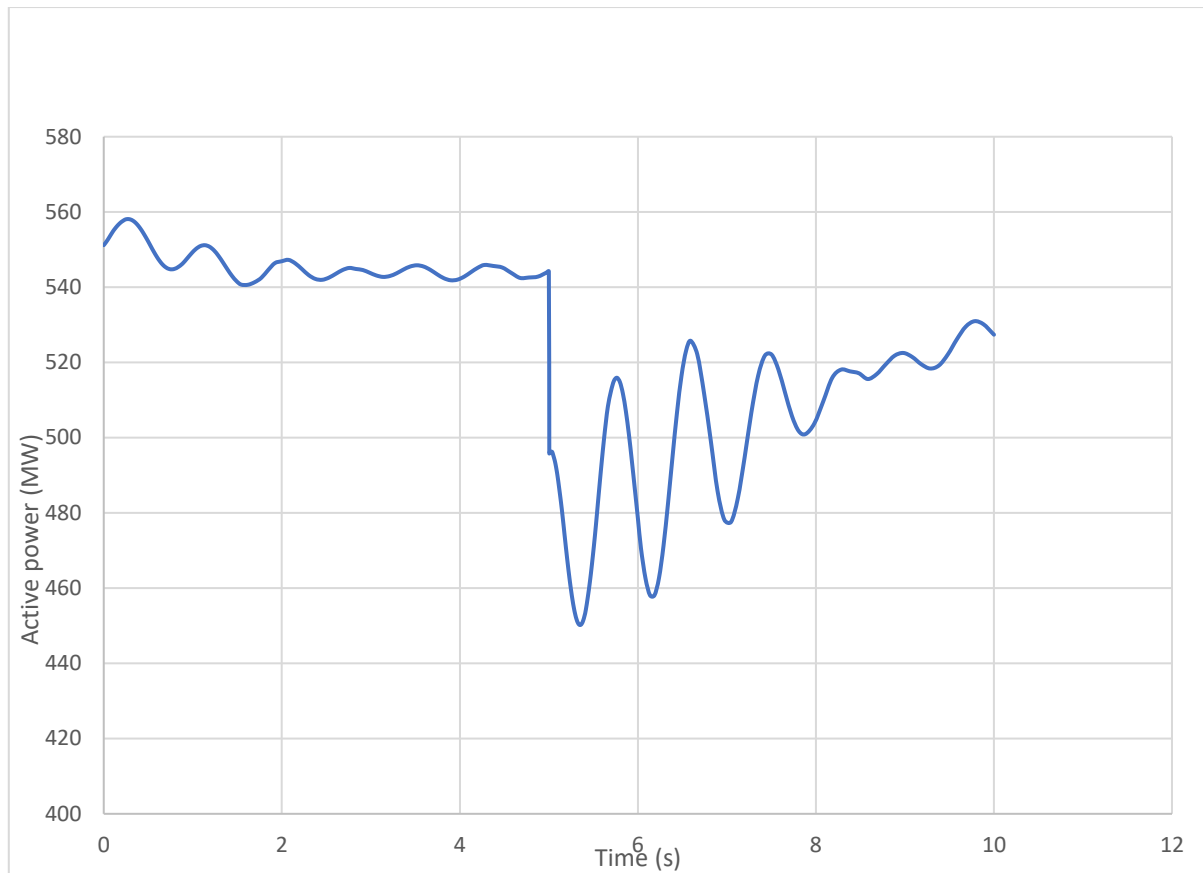


Figure 4.16: The real power drawn by G2 during the load decrease contingency (modified 12-bus network)

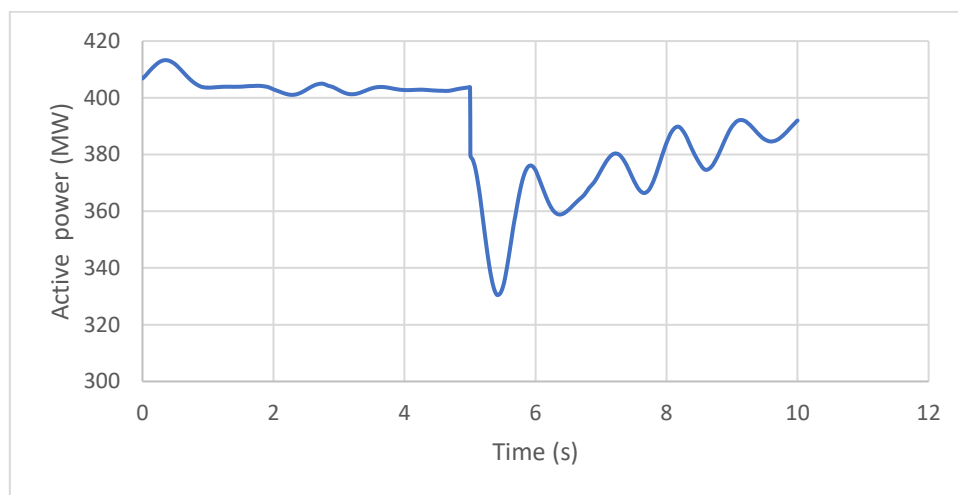


Figure 4.17: The real power drawn by G3 during the load decrease contingency (modified 12-bus network)

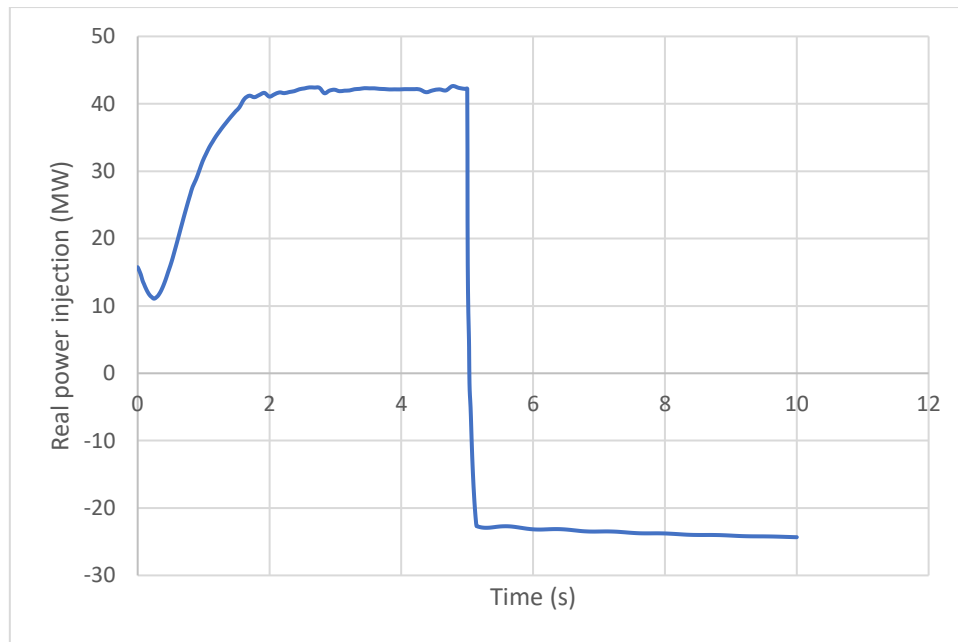


Figure 4.18: The real power drawn by the BESS during the load decrease contingency (modified 12-bus network)

Table 4.10: Frequency levels with respect to network conditions (modified 12-bus network)

Modified 12-bus system	Frequency (Hz)
Without a BESS	51.87
With a BESS	51.40

Table 4.11: Power taken from the network when the power produced was greater than the load (modified 12-bus network)

Power plant	Active power drawn (MW)
G2	94
G3	74
BESS	65

In the load decrease contingency scenario, more power was produced than demanded and therefore the frequency increased. Through the action of the BESS control strategy, the BESS switched to its charging mode, thereby drawing active power from the test system to curtail the rise in frequency and ensure that it remained within the acceptable frequency range. Table 4.10 and Table 4.11 show that the BESS drew a total real power of 65 MW to sustain the frequency at 51.4 Hz. Without the support from the BESS control system, the frequency rose to 51.87 Hz. This was not acceptable, being above the recommended maximum

frequency level based on the grid code. The consequences of an abnormally high frequency in the grid network include a high rotational speed of the generators leading to the destruction of power system equipment, loss of synchronism among the synchronous generators, and voltage instability.

4.4.4 Deployment of the proposed control unit within a 53-bus grid network.

The proposed BESS control was tested within a 53-bus grid network, using the Western Cape modified 53-bus network. The drop in load magnitude was 350 MW, which occurred 5 s into a 10 s simulation. The frequency characteristics and real power taken from the grid during the contingency event are summarized in Table 4.12 and Table 4.13 and Figure 4.19 to Figure 4.22.

Table 4.12: Frequency levels with respect to network conditions (modified 53-bus network)

Modified 53-bus system	Frequency (Hz)
Without a BESS	50.38
With a BESS	50.24

Table 4.13: Power taken from the network when the power produced was greater than the load (modified 53-bus network).

Power plants	Active power (MW)
G 1	58.6
G grid	192.4
BESS	15.29

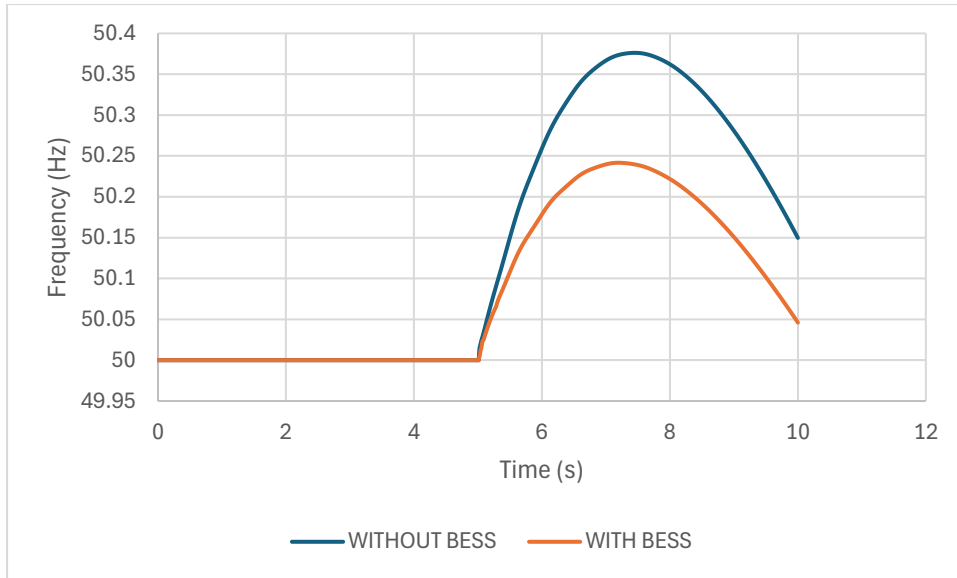


Figure 4.19: Frequency behavior during a 350 MW drop in load (modified 53-bus network).

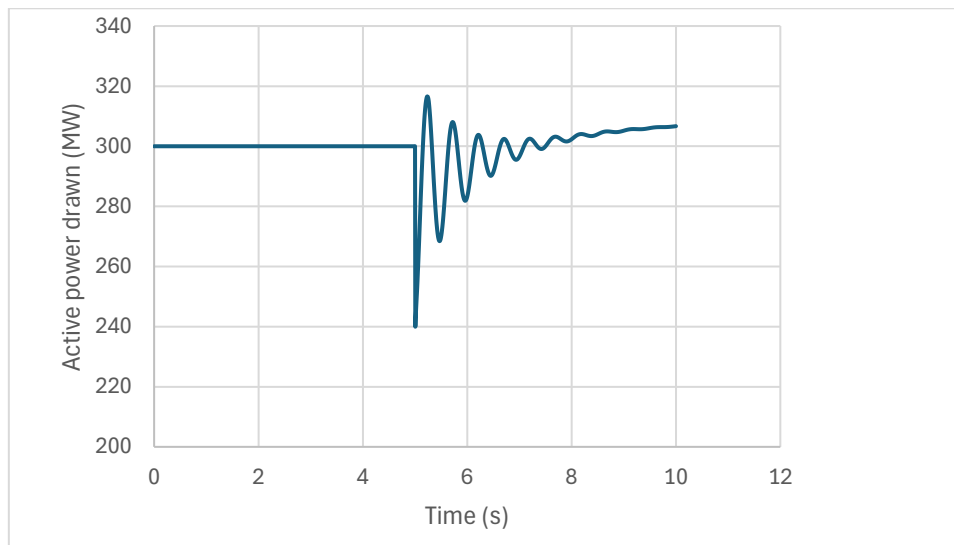


Figure 4.20: The real power drawn by G2 during the load decrease contingency (modified 53-bus network)

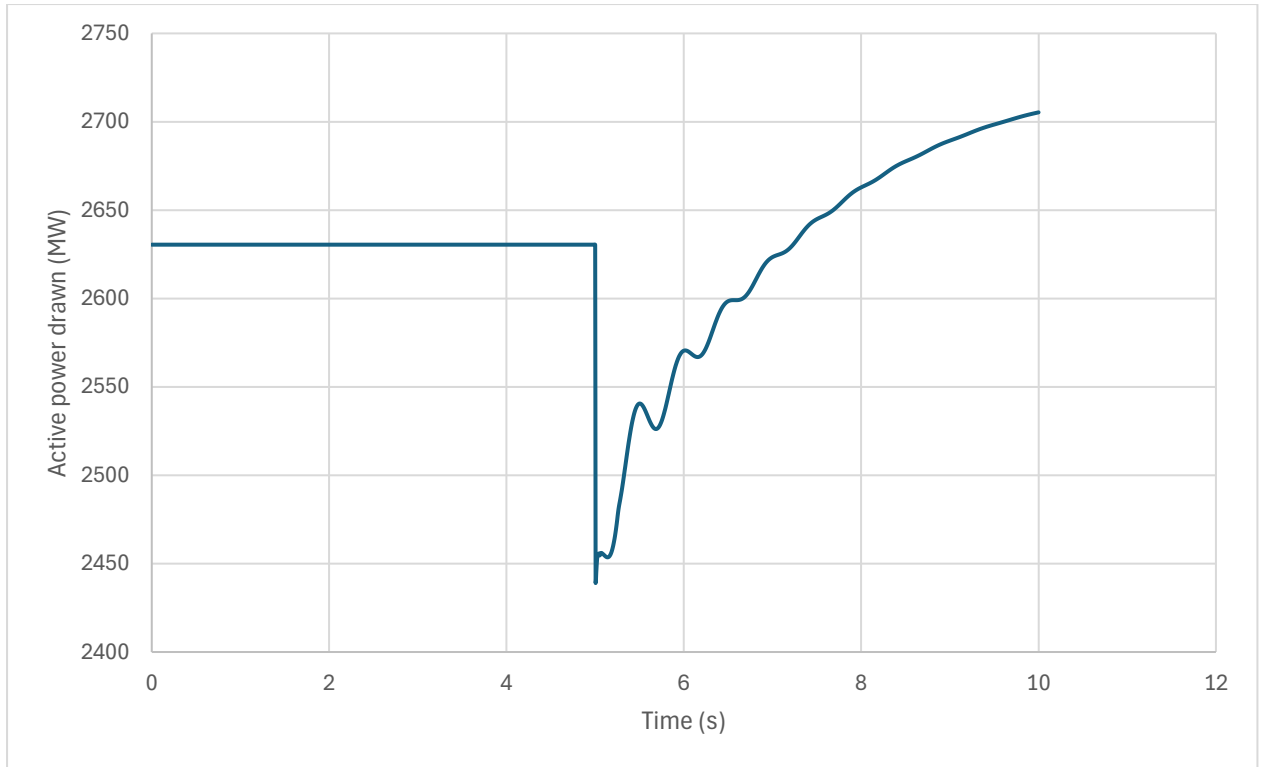


Figure 4.21: The real power drawn by the grid during the load decrease contingency (modified 53-bus network).

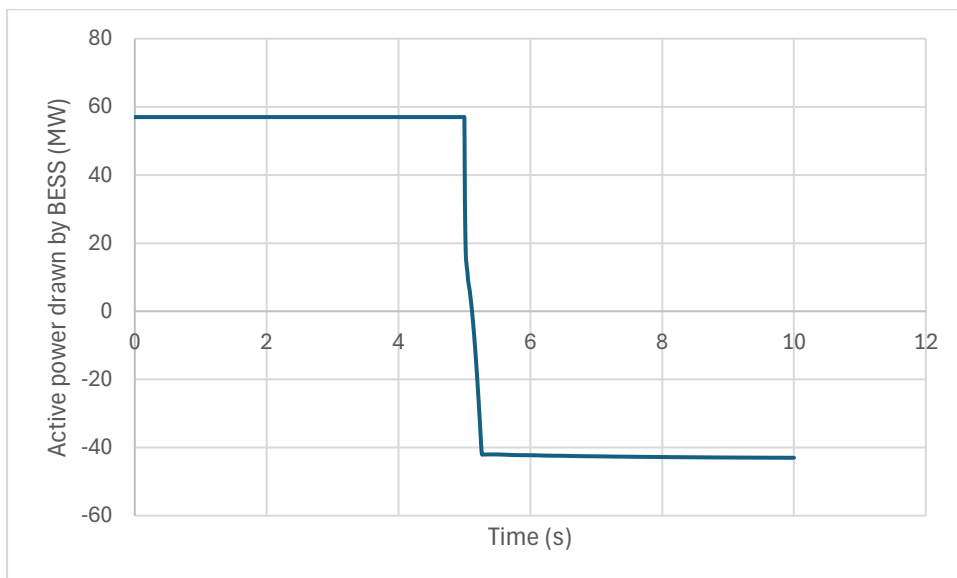


Figure 4.22: The real power drawn by the BESS during the load decrease contingency (modified 53-bus network)

Synchronous generators naturally inject power into the grid during increased load disturbance and absorb power from the grid during load decrease contingency events. However, for the BESS to inject or absorb power during contingencies,

an appropriate control system is required. The results signified that through the suggested approach, the BESS was able to sustain the frequency at an allowable level, taking power from the grid for charging purposes during the drop in the load event. At the instant of the sudden load decrease, the BESS (through the frequency controller actions) operated in its charging mode, thereby drawing about 15.29 MW of real power from the test system. Consequently, this assisted in sustaining the frequency at about 50.24 Hz. The frequency rose to 50.38 Hz without the supportive measures from the BESS. As discussed in section 4.3.4, abnormal frequency levels (i.e., a frequency level above the acceptable threshold) have many negative impacts on the grid network.

4.4.5 Supply of reactive power through the suggested control system

In addition to enabling the provision of support for frequency regulation during both load increase/decrease scenarios, the suggested control approach for the BESS could also facilitate the supply of reactive power in the test system. This service was only activated when the need arose in the grid. Whenever the function was not needed in the test system, the service could be deactivated. With this control system functionality activated in the grid, the magnitude of the voltage across all the buses in the test system could be improved, thus mitigating deviations in voltage. By improving the voltage of every bus in the studied network, the overall stability was enhanced. To show the ability of the BESS control to perform this function, the reactive power functionality was triggered in a simulation of 10 s. Figure 4.23 is a diagram showing approximately 3.63 MVar of reactive power released by the BESS into the grid through the newly designed BESS control. This service by the BESS made a substantial contribution toward the improvement of the voltage magnitude in all buses, as shown in Figure 4.24. For a scenario where this service is not required, the functionality could be deactivated, and zero reactive power would be supplied, as shown in Figure 4.25.

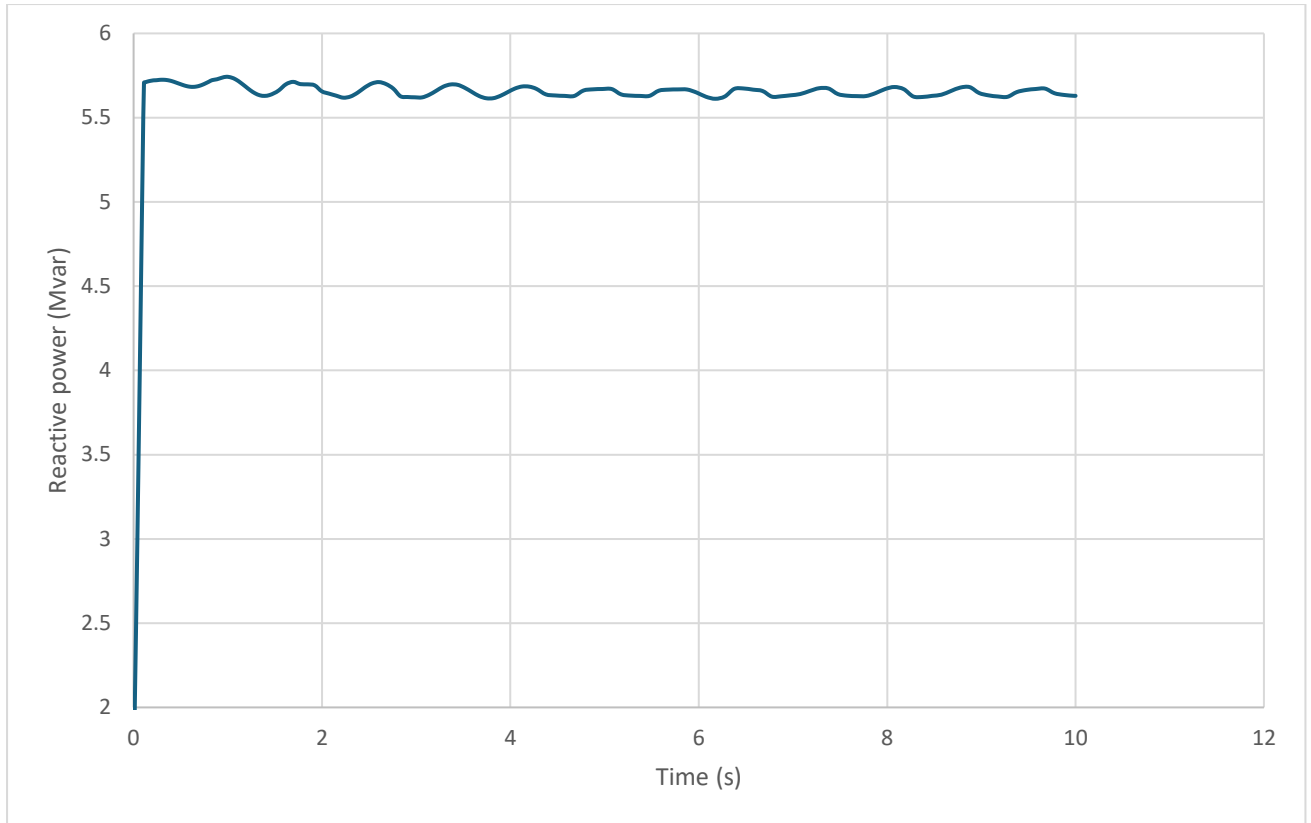


Figure 4.23: The supply of reactive power from the BESS using the suggested technique

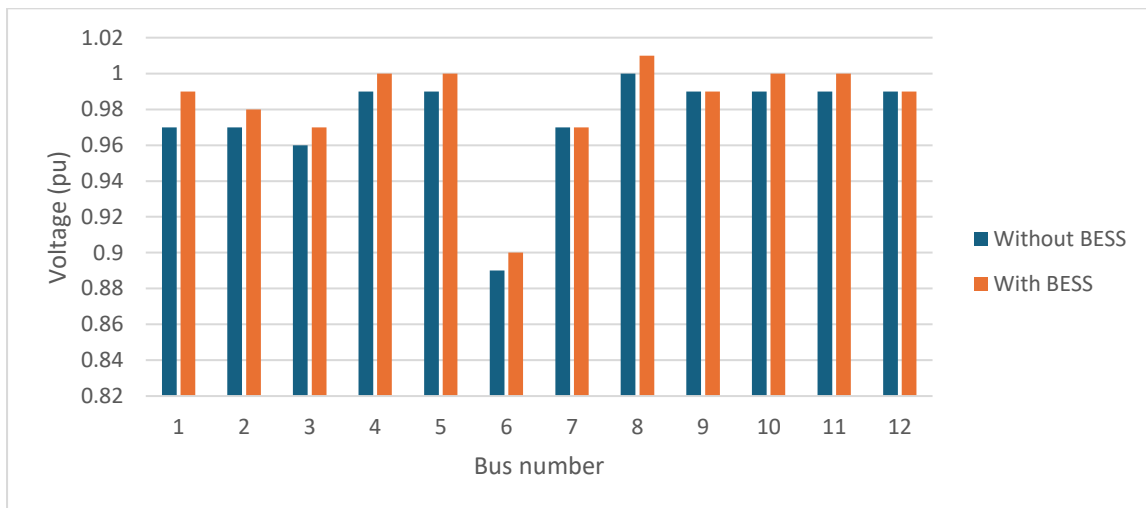


Figure 4.24: Improvement in the voltage profile due to the reactive power supplied by the BESS

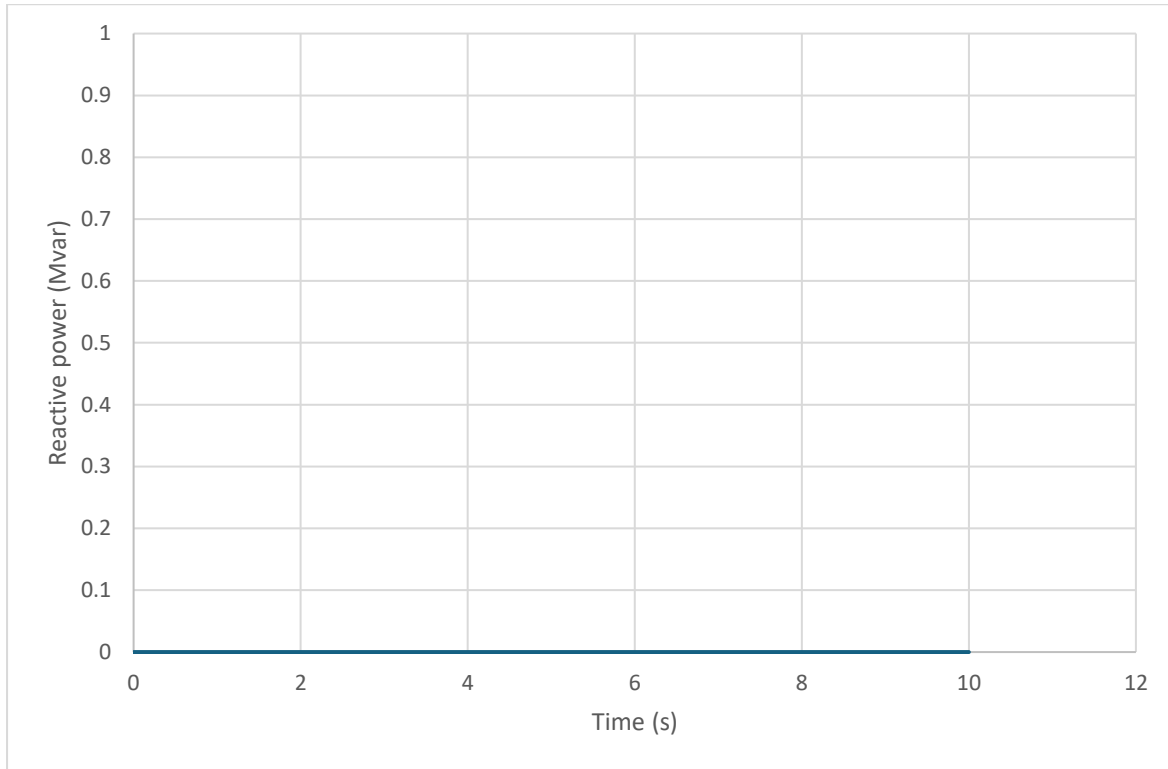


Figure 4.25: Deactivation of the reactive power functionality in the control system (i.e., no reactive power supplied)

4.4.6 Minimization of power losses when using a BESS with the suggested approach

The newly designed BESS control presented in this thesis enables the supply of both real and reactive power. For the minimization of power losses, the position of BESS installation in the grid is crucial. If the BESS is not optimally located, increased losses may be experienced in the electricity grid. Thus, in addition to controlling the BESS to deliver real power, to realize the goal of minimizing the real power losses, the optimal BESS location should also be determined. This point of integration of the BESS into the grid network affects the real power losses. This variability of power losses with respect to the BESS location was demonstrated by deploying the designed control for the supply of real power when the BESS was integrated successively into all the buses in the network. Without the BESS, the real power losses were 26.08 MW. However, when the location of BESS integration into the grid was changed, the total power losses also changed. Table 4.14 shows this variability of real power losses with respect to the BESS point of connectivity, while Figure 4.26 presents a pictorial representation of this comparison.

Table 4.14: Power losses with respect to BESS locations.
(modified 12-bus network)

Bus number for the BESS location	Real power losses (MW)
1	26.08
2	28.94
3	24.17
4	24.13
5	24.03
6	30.27
7	25.94
8	24.29
9	26.08
10	28.96
11(LV bus)	NO BESS placement
12	30.30

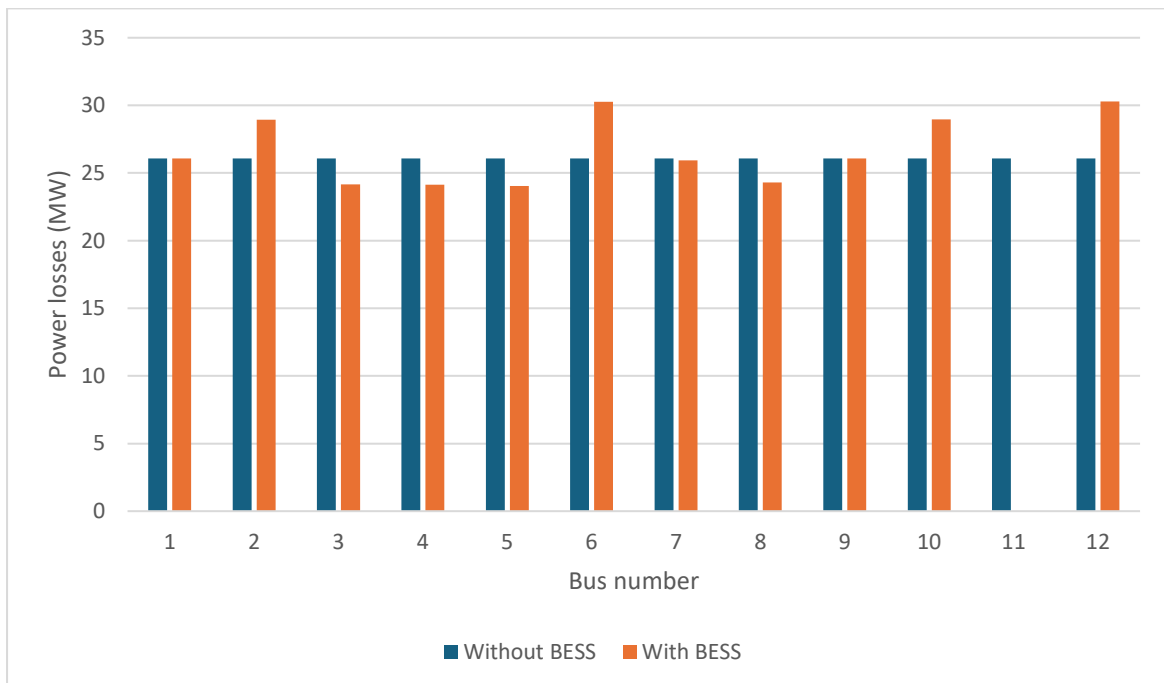


Figure 4.26: Real power losses in the grid at different BESS positions (modified 12-bus network).

Therefore, to deploy a BESS for power loss reduction, the optimal location is very important. This can be achieved using a metaheuristic optimization method or other convenient approach.

4.5 Summary

In Chapter 4, a BESS control system was designed for the multi-purpose functions of providing frequency nadir support during contingency events, the reduction of real power losses, and the mitigation of voltage deviations.

The design calculations for the four sub units of the control system namely the battery model, the frequency controller model, the charge controller model and the active and reactive power controller model were carried out resulting in knowing the appropriate size of the parameters of all the sub units of the control system.

Also, strategic approaches for the actualization of the designed BESS control method in the DIgSILENT Power Factory environment were explained.

Finally, the designed BESS control system was tested by using two test systems. They are a smaller test system (the 12-bus test system) and a larger test system (the 53-bus Wester Cape network). The results from both scenarios demonstrated the effectiveness of the suggested method.

5. USING A BESS TO PROVIDE FREQUENCY NADIR SUPPORT DURING CONTINGENCY EVENTS UNDER DIFFERENT GRID CONDITIONS

The application of a BESS for frequency nadir support during contingency events under different grid conditions was investigated in this chapter. The different network conditions investigated were the length of the lines, wind generation variability, the magnitude of the power mismatch, variation in wind penetration, BESS capacity, and the magnitude of the sudden change in load.

5.1 The impact of BESS capacity on the provision of frequency nadir support during a contingency event

The impact of BESS capacity on the provision of frequency nadir support during contingency events in a grid network was examined. Alhejaj and Gonzalez-Longatt [23] reported that a grid-scale BESS larger than 50 MW, when integrated into a grid, is capable of providing ancillary services in the grid. In this study, BESS capacities were selected in the range of 50 to 110 MW with increments of 20 MW. A contingency event with a 300 MW increase in load with different BESS capacities (50 to 110 MW) connected to the grid was triggered at 5 s in a 10 s simulation. Table 5.1 displays the outcomes of the simulations when different BESS capacities were deployed, while Figure 5.1 shows the frequency characteristics during a power mismatch event. Additionally, Figure 5.2 shows the correlation between the BESS capacities and the minimum frequency attained (frequency nadir).

Table 5.1: Different BESS capacities and frequency characteristics of the test system

BESS size (MW)	RoCoF (Hz/s)	Minimum frequency (Hz)
50	-0.43876	48.98
70	-0.38039	49.20
90	-0.35920	49.32
110	-0.33778	49.44

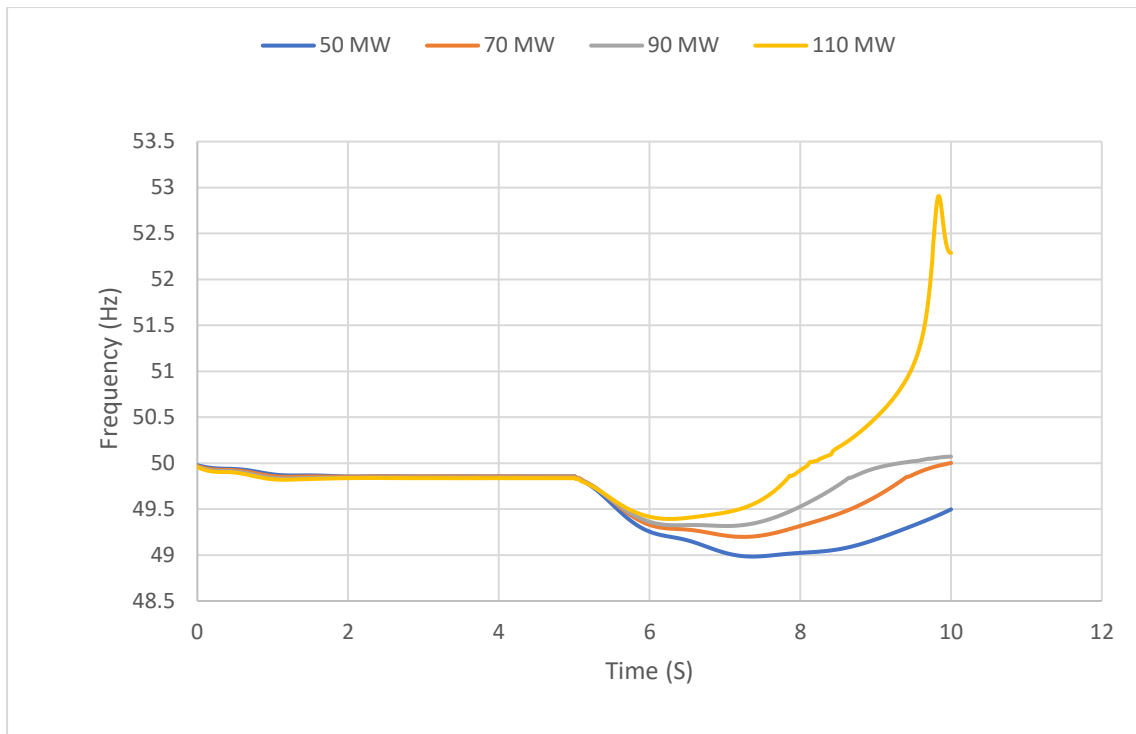


Figure 5.1: The frequency characteristics with different BESS capacities

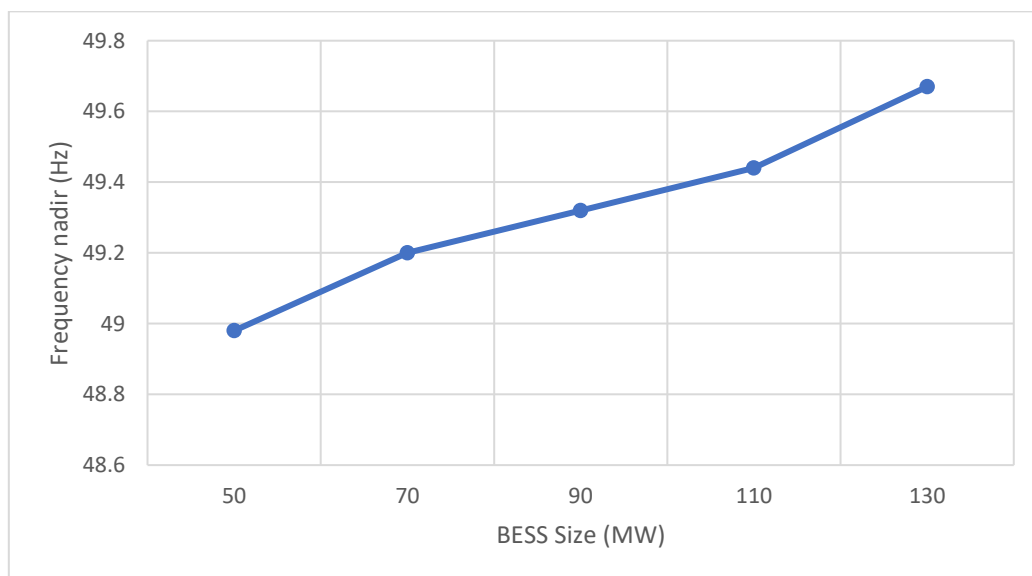


Figure 5.2: The association between different BESS capacities and frequency nadirs.

The results revealed that the BESS capacity affected the frequency nadir and the RoCoF. The greater the BESS capacity, the better the frequency nadir improvement and RoCoF reduction. The reduction in the magnitude of the RoCoF as the capacity of the BESS increased resulted in an improvement in the

system inertia. It is known that there is an indirect relationship between system inertia and RoCoF, therefore, deploying a BESS with a greater capacity will strengthen the system inertia. This is already low in situations when there is a high renewable energy penetration. Although increasing the BESS capacity improved the system inertia and the frequency nadir, the cost of the BESS increased. Thus, determining the optimal capacity of a BESS is essential to maintain the frequency nadir within the acceptable threshold.

Finally, it should be noted that the increase in frequency from 9 s in the simulation was as a result of a lower RoCoF value. RoCoF is inversely proportional to frequency. At a lower RoCoF, the frequency is high. Also, the absence of a primary frequency control may have accounted for the increase in frequency as our study primarily focused on the characteristics of the frequency nadir.

5.2 The impact of line lengths on the frequency nadir support provided by the BESS during a contingency event

An investigation was conducted to determine how the lengths of transmission lines affect the frequency support provided by the BESS during a contingency event. The transmission line lengths varied, as shown in Table 5.2. A power mismatch arising from an additional 300 MW increase in load was triggered at 5 s during a 10 s simulation. The summary of the results for each length considered are displayed in Table 5.2.

Table 5.2: Effect of transmission line length on frequency response characteristics

Line lengths (km)	Minimum frequency (Hz)	RoCoF (Hz/s)
L	49.39	-0.5424
1.5 L	49.73	-0.3268
2.0 L	49.85	-0.1304

Note: L* signifies the initial length of the line

Table 5.2 shows that by increasing the transmission line lengths, the RoCoF is reduced and consequently the frequency nadir improves. Thus, the deployment of the BESS for frequency nadir support in a long transmission network may not be effective because of the inherently low RoCoF. Because the RoCoF is low, the system frequency will not rise/fall rapidly during contingency events.

There are also practical implementation constraints. First, a long transmission line will result in increased active power losses and voltage drops. Stability issues may also arise as a result of increases in the inductance and capacitance of the line. Finally, it may not be economically profitable to implement long transmission lines.

5.3 Provision of frequency nadir support during a contingency event with varying levels of grid inertia.

An investigation was conducted to determine how varying levels of grid inertia affect the frequency nadir support supplied by a BESS. To vary the grid inertia, the number of synchronous generators should be decreased as additional renewable energy sources are added to the grid. Therefore, as the grid penetration of renewable energy resources increased in the network, the system inertia decreased. In this study, five levels of wind power penetration were considered in the test system. Each level was evaluated as the total power generated from the wind power plants divided by the overall generation. The result was then expressed as a percentage. For each penetration level, the simulation was initiated for a specified duration of 10 seconds with a load increase contingency triggered at 5 seconds from the commencement of the simulation. The frequency characteristics are summarized in Table 5.3, while the frequency responses are shown in Figure 5.3a (without a BESS in the network) and Figure 5.3b (with a BESS support in the network)

Table 5.3: Summary of the frequency response characteristics.

Wind penetration level (%) (Varying grid inertia)	RoCoF (Hz/s) (Network without a BESS)	F_{min} in Hz) (Network without a BESS)	RoCoF (Hz/s) (Network with a BESS)	F_{min} (Hz) (Network with a BESS)
0	-0.5212	48.55	-0.3456	49.55
13	-0.8012	46.84	-0.3934	49.02
26	-0.8097	46.66	-0.4258	48.99
42	-1.0766	46.10	-0.8195	47.93
56	-1.7035	45.52	-0.9586	47.27

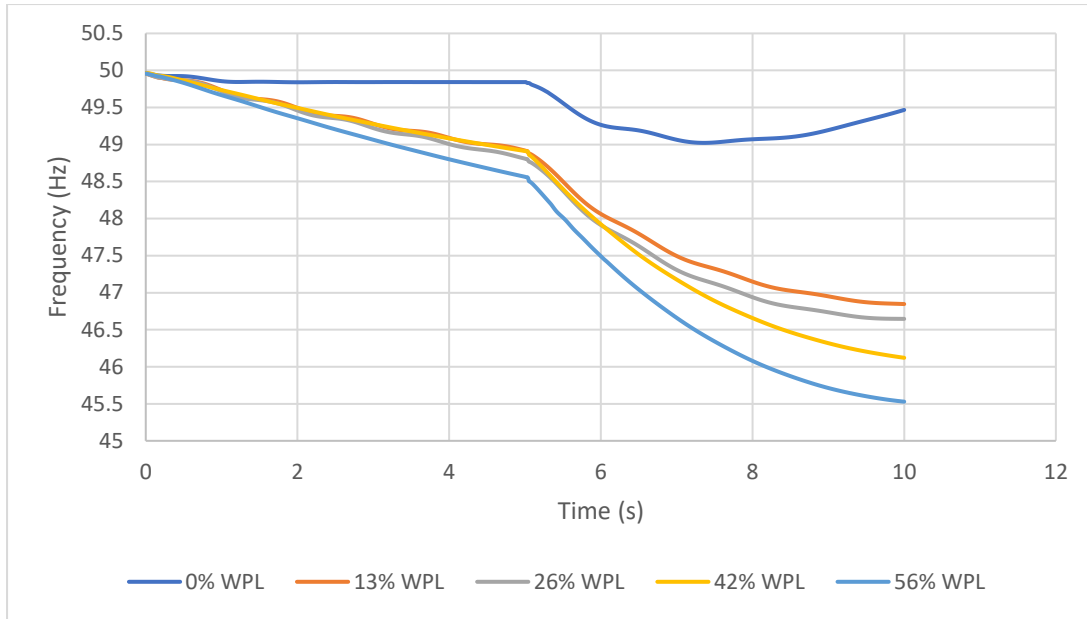


Figure 5.3 (a): The frequency response characteristics (network without a BESS)

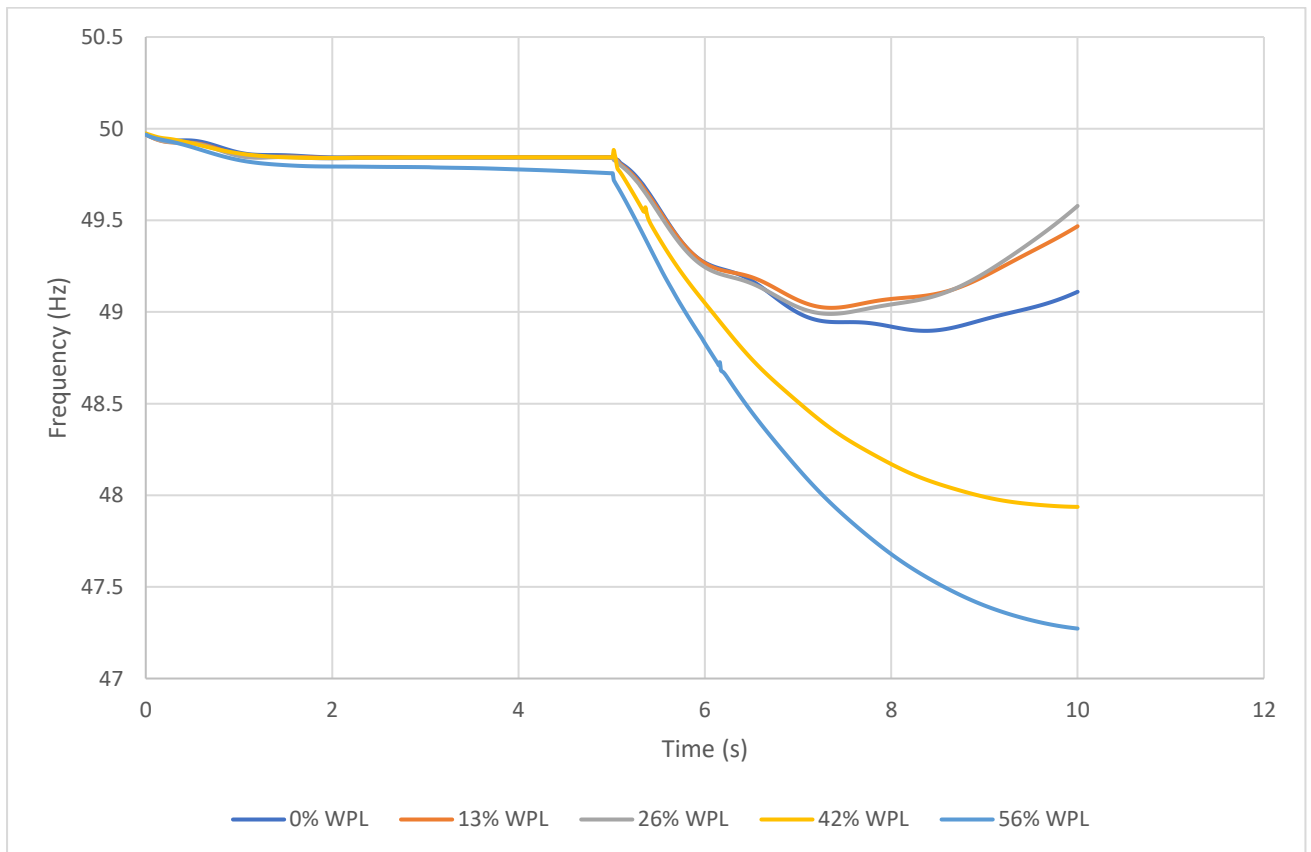


Figure 5.4 (b): The frequency response characteristics (network with a BESS)

There was a substantial enhancement in the frequency nadir and RoCoF compared to when the network had no frequency support, especially when the proportions of renewable energy sources were 13% and 26%. At 26% wind

penetration (without a BESS), the RoCoF was almost twice the value when there was support from a BESS. The consequence of this high RoCoF value was a decline in the frequency nadir, which was 46.66 Hz during the load increase contingency.

As the renewable energy penetration level increased to 42% and 56%, the RoCoF became higher and the support from the BESS could no longer effectively sustain the frequency. Consequently, the frequency nadir fell rapidly to 47.27 Hz at 56% wind penetration. To address this problem, an appropriate penetration level should be adopted when sizing a BESS so that even with a high renewable energy penetration, the BESS would be capable of arresting the frequency decline due to contingencies.

Moreover, more advanced controllers could be deployed to ensure that enough active power is injected/absorbed at the onset of a contingency.

5.4 The impact of variable output generation from wind plants on the frequency nadir support provided by a BESS during a contingency event

Output power variability is one of the drawbacks of renewable energy sources. This is due to the dependence on weather conditions for power generation. The impacts of the intermittency of wind power generation on the frequency nadir support provided by a BESS during a contingency event were therefore investigated. The test system was the modified 12-bus network discussed in section 4.3. For this study, the output power of WPP1 ranged as shown in Table 5.4. Simulations were conducted for each of the WPP1 output generations with a contingency event of 300 MW. Two network conditions were investigated: a network without a BESS and a network with a BESS. The outcomes of the simulation are given in Table 5.4, while the frequency characteristics, with the minimum and maximum power generation from the WPP1, are displayed in Figure 5.4.

Table 5.4: Frequency characteristics under a variable output from WPP1

Variable Power output from WPP1 (MW)	Minimum frequency (without a BESS) (Hz)	Minimum frequency (with a BESS) (Hz)
50	46.84	49.11
70	46.80	49.08
90	46.76	49.03
110	46.72	49.02

130	46.69	49.00
150	46.66	48.99

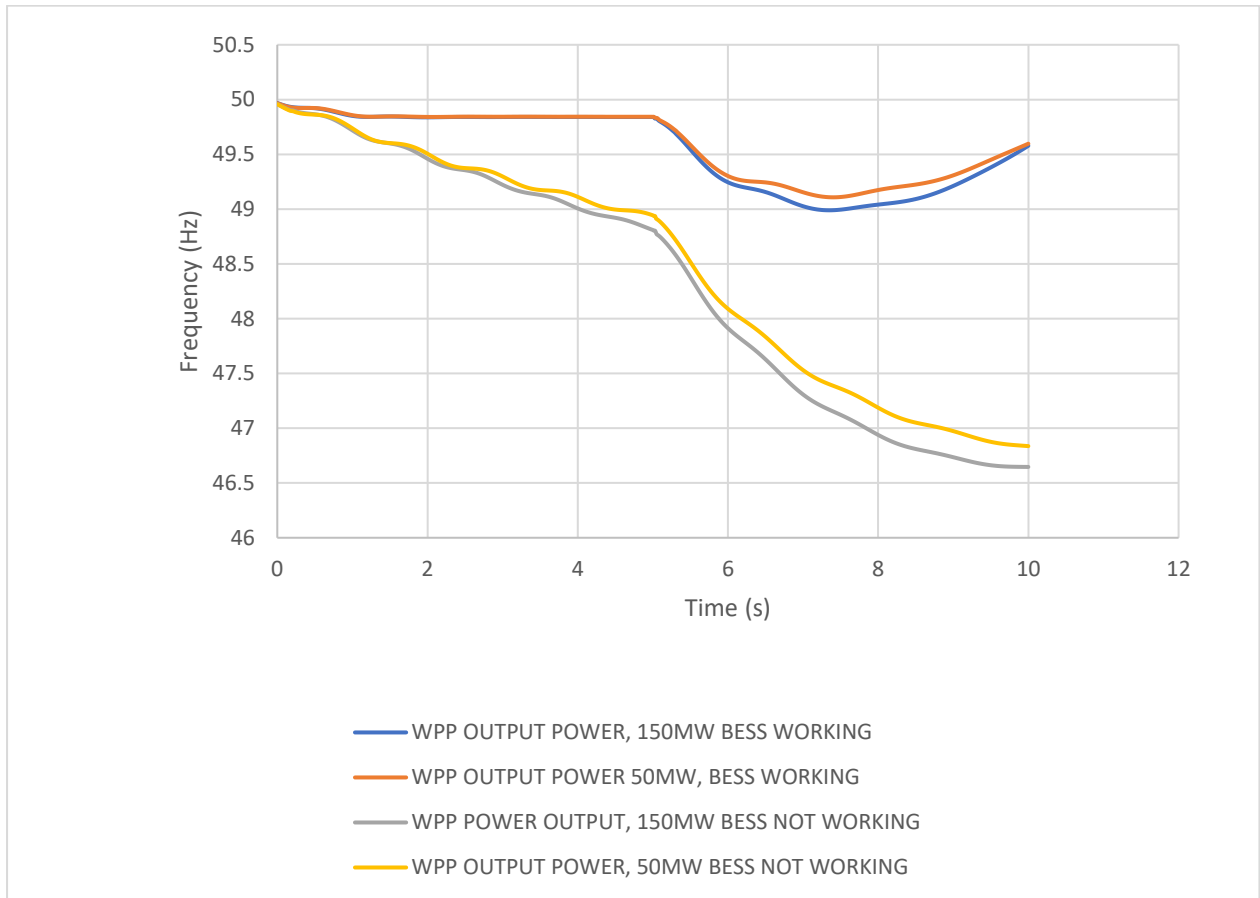


Figure 5.5 : The frequency response characteristics under a variable output from WPP1

From the variable values in Table 5.4, it is evident that variable generation from renewable energy plants does not affect the support from a BESS during a contingency event. In Table 5.4, when the network had a BESS, the lowest frequency reached as a result of the disturbance event was 49 Hz. The frequency nadir did not change appreciably as the generation output of WPP1 changed from 50 to 150 MW. When the test network had no BESS model supplying frequency support, the frequency nadir remained at about 47 Hz as the output generation from the WPP1 changed between 50 to 150 MW. These outcomes were in alignment with previous studies, which have emphasized that renewable energy sources do not supply inertia (which supports the frequency nadir during a contingency event), even when they are controlled. Figure 5.5 to Figure 5.7 show the active power injections at the onset of the contingency, while Figure 5.8 and Figure 5.9 show that no power was injected in the wind power plants at the onset of the contingency.

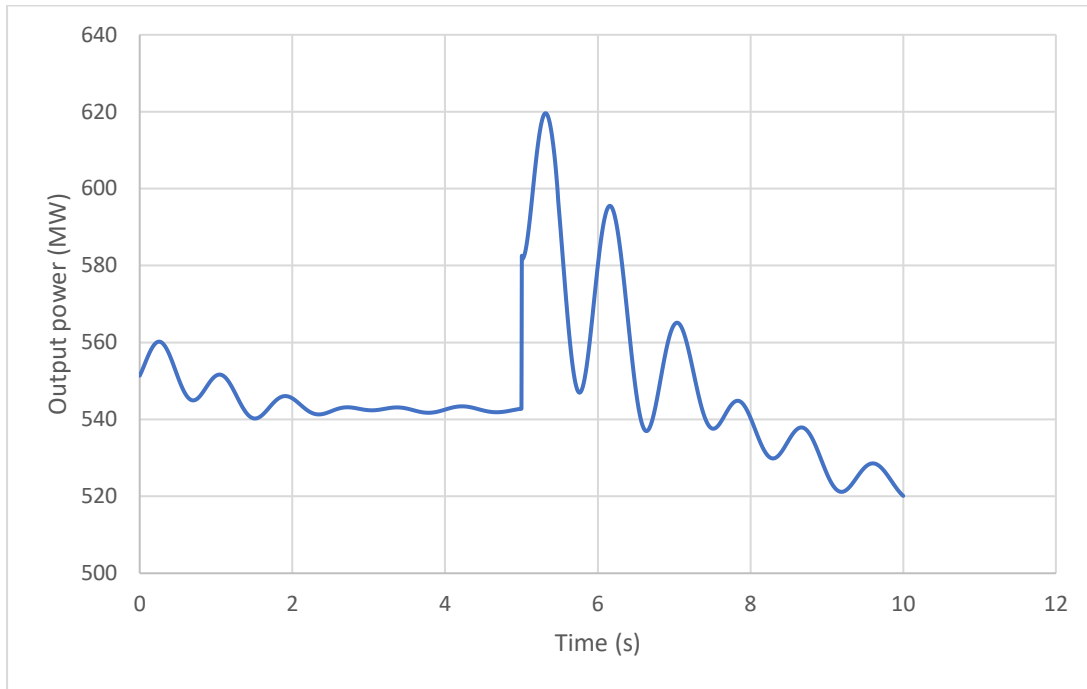


Figure 5.6: The real power injection by G2 at the onset of a contingency event

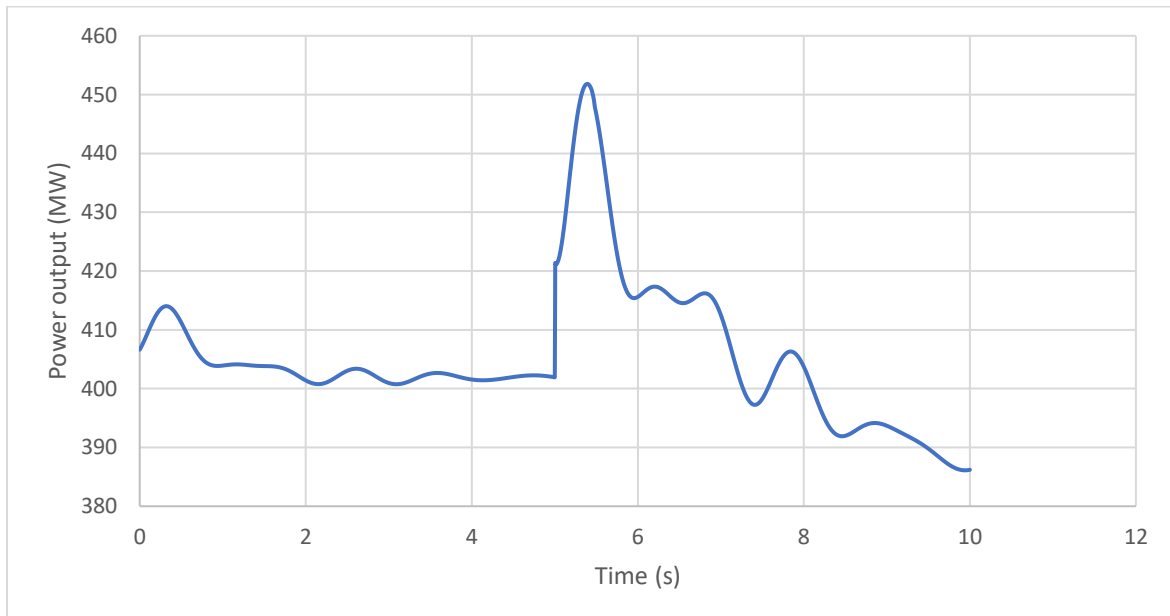


Figure 5.7: The real injection by G3 at the onset of a contingency event

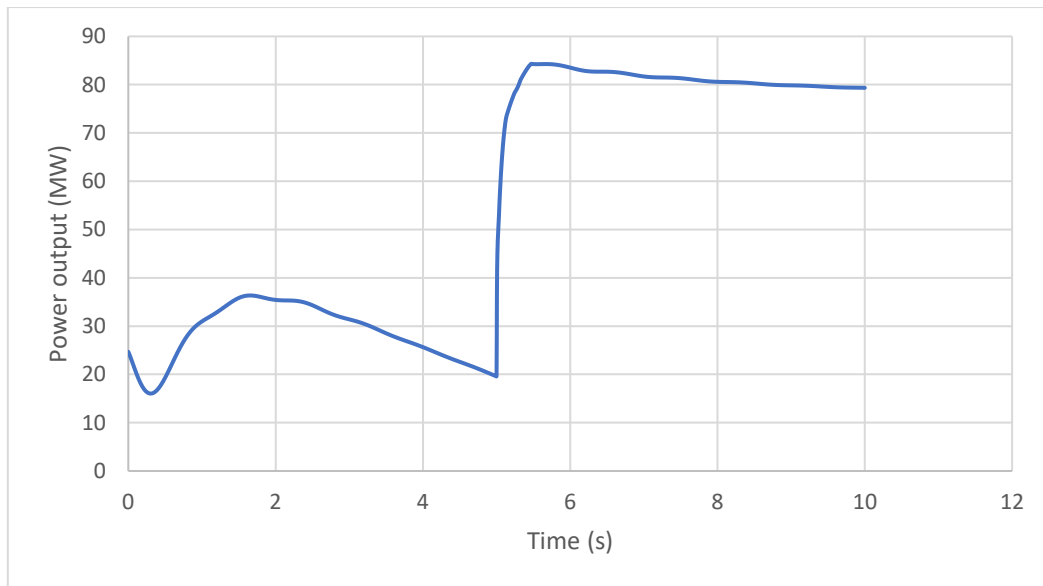


Figure 5.8: The active power injection by the BESS at the onset of a contingency event

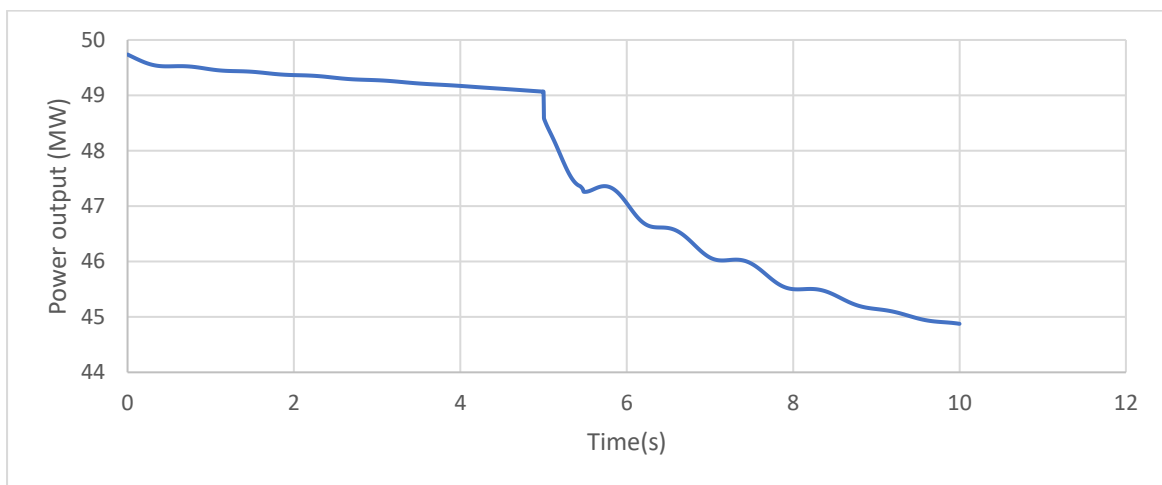


Figure 5.9: No active power injection by WPP 1 at the onset of a contingency event

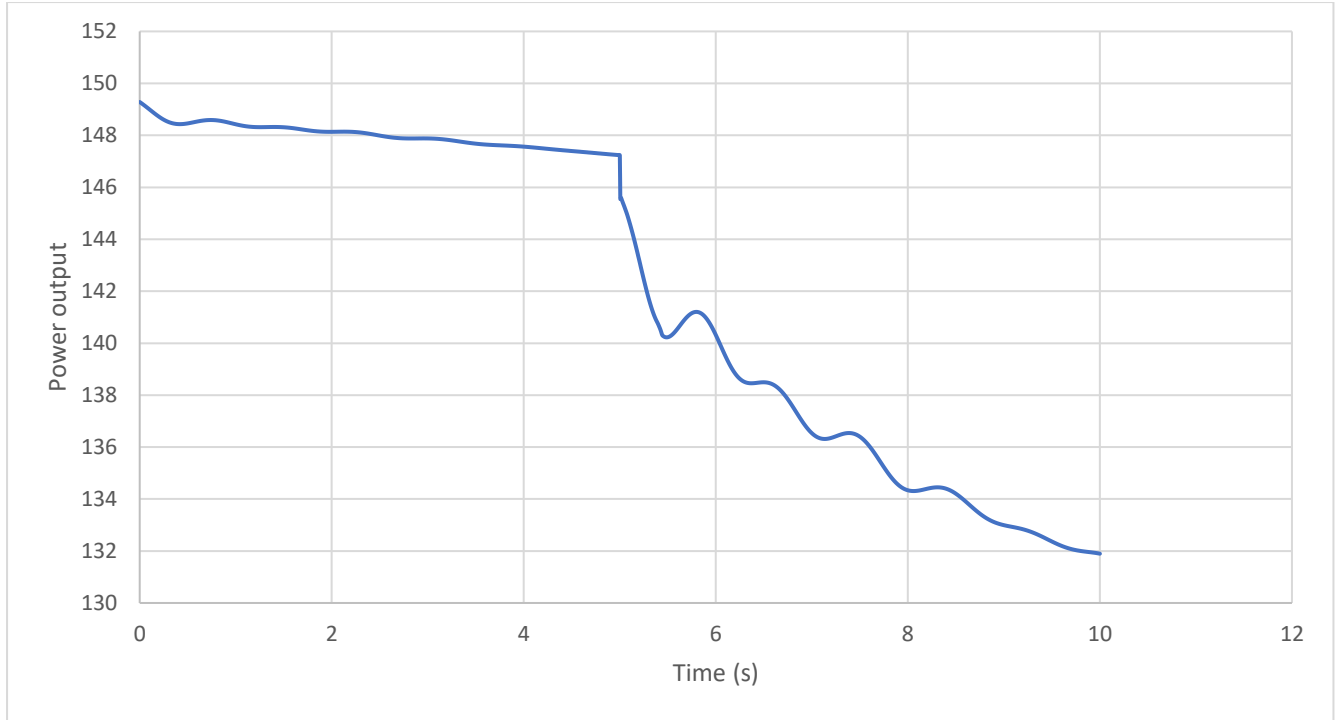


Figure 5.10: No active power injection by WPP 2 at the onset of a contingency event

In conclusion, with the support from the BESS, the frequency was sustained at 49 Hz during a frequency disturbance event of 300 MW, while the power output from WPP1 varied from 50 to 150 MW. This demonstrated that the BESS was effective in making support available despite the intermittency of wind power generation.

5.5 The impact of the size of a power mismatch on the frequency nadir support provided by a BESS during a contingency event

The impact of the size of a power mismatch on the frequency nadir support provided by a BESS during a contingency event was investigated. In Table 5.5, ΔP_L (MW) is the size of the power mismatch, while the real power injected by the BESS during the mismatch event is $P_{O(PC)}$ (MW). The power mismatch applied in this study ranged from 30 to 375 MW. With respect to the variable values in Table 5.5, it was evident that the magnitude of the power mismatch had an impact on the support offered by the BESS during a contingency event. As the magnitude increased, the BESS responded to compensate for the power deficit by injecting more active power, as shown in Table 5.5 and Figure 5.10. However, the BESS reached its maximum power injection of approximately 62.36 MW with a power imbalance of 105 MW. As the power imbalance increased above 105 MW, the BESS could not improve on the real power released. Consequently, the RoCoF increased, and the frequency nadir deepened. This shows that the capacity of the PC can limit the active power injected by the BESS. Thus, the BESS could not

inject power into the grid that is beyond the PC power limit, although the BESS capacity was increased. Under these conditions, the BESS may not provide effective support to keep the frequency nadir within an acceptable range according to the grid codes.

Table 5.5: Summary of the network responses due to an increase in the power imbalance

ΔP_L (MW)	$P_{O(PC)}$ (MW)	RoCoF (Hz/s)	F_{MIN} (Hz)
30	14.74	-0.11135	49.91
75	44.16	-0.13478	49.83
105	62.36	-0.15843	49.79
150	62.05	-0.22734	49.70
180	61.57	-0.27307	49.62
225	60.78	-0.33868	49.52
255	60.62	-0.38122	49.46
300	59.67	-0.44773	49.38
330	59.03	-0.49401	49.34
375	58.56	-0.56223	49.29

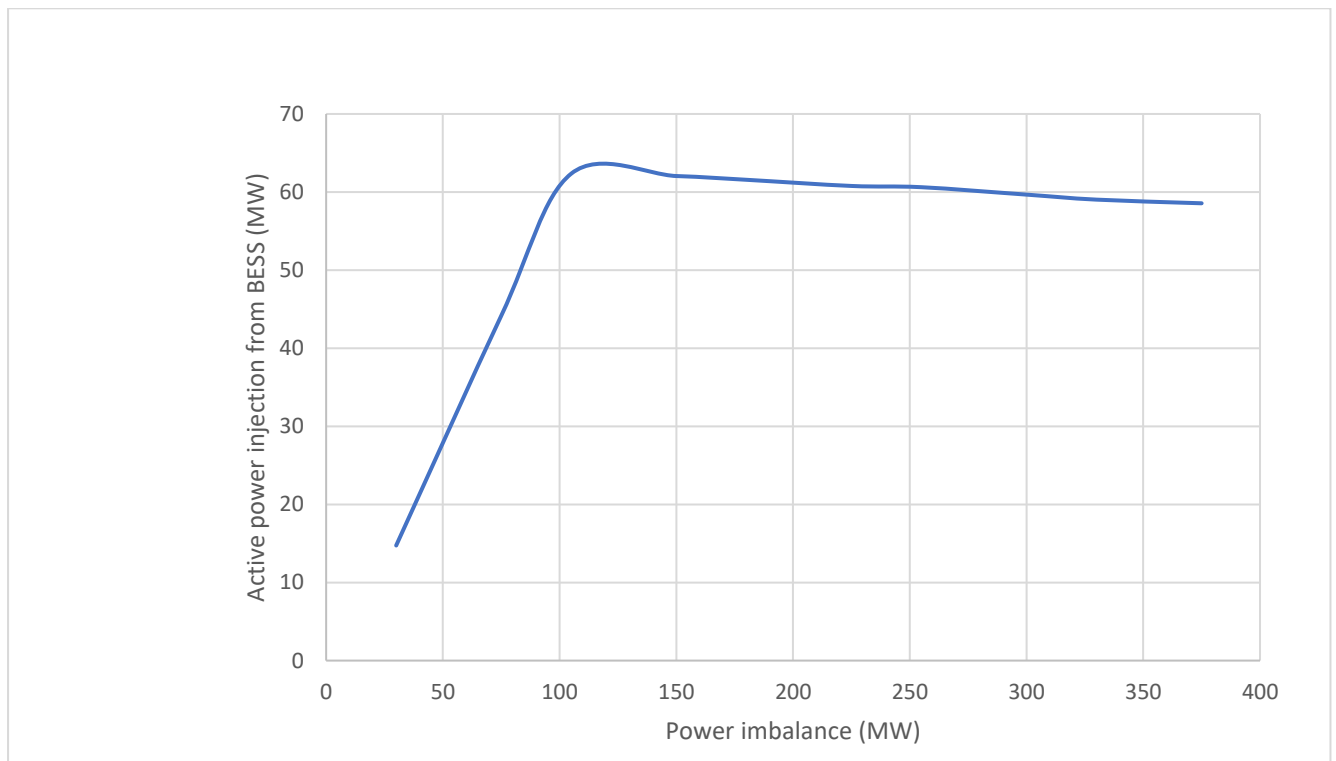


Figure 5.11: Variation of the frequency nadir as the power imbalance increases

5.6 Summary

Chapter 5 investigated the impacts of line lengths, BESS capacity, the magnitude of the power mismatch, the variable output of wind generation, and the varying levels of grid inertia on the frequency nadir support provided by BESS during a contingency event. The results showed that both frequency nadir and RoCoF are affected by the afore-mentioned network conditions.

Firstly, the investigation showed that when the capacity of BESS was increased, more active power was injected by BESS into the grid during contingency events. This compensated for the power deficit and consequently the frequency nadir during the power system disturbance event was improved.

Moreso, the study revealed the impact of transmission line lengths on the rate of change of frequency during power system frequency disturbance event. Results showed that when the transmission line length was doubled, the rate of change of frequency was greatly reduced resulting in a great improvement in the frequency nadir.

Besides, results from the study confirmed a linear relationship between the magnitude of power imbalance and the active power injected by BESS during contingency event. That is, as the power imbalance increases, BESS injects more active power to compensate for the active power deficiency. However, this relationship exists as long as the capacity of the power converter is not exceeded.

6. CONCLUSIONS

In this study, novel methodologies for determining the optimal location, size, and control of a BESS for multiple functions were established. The optimal placement method uses mathematical optimization formulations based on real power injection, inertia contributions, and RoCoF, while the sizing methodology deployed RoCoF, a regression analysis, and the DSO algorithm. The control of the BESS for multiple functions was achieved through the appropriate design of controllers, with implementation accomplished using the DIgSILENT Power Factory software.

By deploying the proposed novel BESS placement strategy for frequency nadir support during contingency events and using a test system, it was found that by placing BESS at the optimal location (bus 61 in the test system), the RoCoF decreased by about 44.4% thereby improving the frequency nadir from 49.49 to 49.60 Hz. In a similar development, by installing the BESS at the optimal location (bus 29, in the test system) for the reduction of real power losses and mitigation of voltage deviation, the total real power losses were reduced by over 50% and the voltage magnitude of all buses in the test system were enhanced to the acceptable threshold according to the grid.

Additionally, the robustness of the BESS novel sizing technique was tested using a network with 50% renewable energy penetration. The frequency nadir during a significant power mismatch was improved from 59.15 to 59.60 Hz. Thus, signifying the ability of the BESS to sustain the frequency nadir within acceptable limits amidst a high penetration of renewable energy sources in the grid network. Once its optimal capacity was determined, the BESS was deployed to mitigate the voltage deviations that occurred as a result of the variability of power generation from renewable energy in the test system. Eight buses in the test system were found to have a voltage magnitude (0.895 to 0.948 pu) below the acceptable limit. However, through the use of the optimal BESS capacity, the voltage deviation in the eight buses was mitigated, thereby enhancing the voltage level of all the buses in the test system to an acceptable magnitude.

Furthermore, using the proposed methodology, a reactive power supply of 3.63 MW was delivered by the BESS to the grid.

More so, the impacts of BESS size, transmission line lengths, size of power imbalance and varying grid inertia on the power system frequency parameters have been investigated.

In conclusion, using the suggested methodologies, the BESS was optimally sized, placed in the optimal location in the grid, and controlled for the multiple functions

of provision of frequency nadir support during a contingency event, reduction of real power losses, mitigation of voltage deviations and the supply of reactive power in a grid network with a high renewable energy penetration.

6.1 Response to the research questions.

The responses to the research questions given in section 1.6 are provided here.

1 What is the optimal size of the EES selected for use in the power system grid network?

Through the novel optimal sizing methodology for the BESS discussed in section 3, the optimal size of the BESS for the multiple functions of provision of frequency nadir support during a contingency event, reduction of power losses, and mitigation of voltage deviations was 145 MW for the study test system. This BESS optimal capacity was deployed for the aforementioned services in the grid network, and satisfactory results were obtained.

2 What is the optimal location of the EES in the power system grid network, and how will it be determined?

This question was answered in Chapter 2, where the optimal location for frequency support for the test system was found to be bus 61. The simulation results revealed that by placing the BESS at that location, the RoCoF during a contingency event was significantly reduced (by about 44.4%), thereby improving the frequency nadir from 49.49 to 49.60 Hz. Similarly, using the proposed placement techniques, the optimal position for the reduction of real power losses and mitigation of voltage deviation for the test system was found to be bus 29. By installing the BESS at this optimal location, real power losses were reduced by over 50%, and the voltage profile of all buses in the test system was improved to an acceptable magnitude according to the grid code.

3 What control methodology will be deployed for the implementation of the multiple functions of frequency nadir support during a contingency event, reduction of power losses, and mitigation of voltage deviations?

The control methodology deployed for the implementation of frequency nadir support during a contingency event, reduction of real power losses, and mitigation of frequency deviations was designed using proportional integral-based controllers. This was tested, and the results were satisfactory.

6.2 Validation of the proposed hypothesis

The proposed hypothesis, given in section 1.4 was:

"The multi-purpose applications of a BESS for frequency nadir support during a contingency event, reduction of real power loss, and mitigation of voltage deviation will result in the full utilization of the BESS (with enhanced economic benefits). This will also reduce some of the challenges associated with the intermittent nature and high penetration of renewable generation (wind and solar photovoltaic) in a power system grid network. This will increase both the system frequency stability and voltage stability and ensure the maximum utilization of renewable generation through the appropriate balancing of generation and load."

In this study, it was proven through the proposed methodologies that a BESS was able to: (a) provide frequency nadir support during a major contingency event, with the frequency nadir maintained within the acceptable limits (according to grid codes), and (b) reduce power losses by about 50%, and improve the voltage profile for all the buses in a power system network with a high renewable energy penetration.

6.3 Recommendations for future work

The following are potential ideas for future work:

- 1 The provision of frequency support by the BESS proposed in this study focused only on the frequency nadir. In future work, the control system could be improved to provide support not only for the frequency nadir during a contingency event, but also to ensure the restoration of system frequency to a nominal value after a contingency event.
- 2 The multiple functions (frequency nadir support during contingency events, reduction of power losses, and mitigation of voltage deviations) provided by the BESS in this study were all power-based applications. More work should be conducted to explore the capability of providing both power-based functions and energy-based services, such as load-levelling and peak-shaving.
- 3 The control of active and reactive power was achieved through the use of PI controllers. The application of advanced and AI-based controllers for real and reactive power control should also be investigated.
- 4 Further work should be conducted to validate the proposed approach using hardware-in-the-loop (HIL) simulations.

7. REFERENCES

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8. AUTHOR’S PUBLICATIONS FROM THE THESIS

Published Journal Papers

- 1. Okafor Chukwuemeka Emmanuel and Komla Folly (2024),** “Design and Implementation of a Control System for Multifunctional applications of a Battery Energy Storage System (BESS) in a Power System Network,” *Cleaner Energy Systems*, 9 (December 2024): 1-24,

<https://doi.org/10.1016/j.cles.2024.100153>

2. **Okafor Chukwuemeka Emmanuel** and Komla Folly (2024), “Optimal sizing of Battery Energy Storage System (BESS) for multiple applications using regression analysis and Deep Sleep Optimizer Algorithm,” *Scientific African Journal*, 26 (December 2024): 1-22, <https://doi.org/10.1016/j.sciaf.2024.e02424>
3. **Okafor Chukwuemeka Emmanuel** and Komla Folly (2023), “Optimal Placement of a Battery Energy Storage System (BESS) In a Power System Network for Frequency Support during Contingency,” *Energy Reports*, 10 (November 2023): 3681-3695, <https://doi.org/10.1016/j.egy.2023.10.017>
4. **Okafor Chukwuemeka Emmanuel**. and Komla Folly, (2023), “Provision of Additional Inertia Support for a Power System Network Using Battery Energy Storage System (BESS),” *IEEEAccess*, 11 (July 2023): 74936-74952, DOI: [10.1109/ACCESS.2023.3295333](https://doi.org/10.1109/ACCESS.2023.3295333)

Journal Paper in progress

5. **Okafor Chukwuemeka Emmanuel**, Saheed Lekan Gbadamosi, Senthil Krishnamurthy, Mukovhe Ratshitanga, and Prathaban Moodley, (2025) “Techno-economic analysis of battery storage technologies in distribution networks with integrated electric vehicles and solar PV systems” *Energy Reports* (accepted for publication, not yet published at the time of Thesis submission)

Published, Chapter in a Book

6. **Okafor Chukwuemeka Emmanuel** and Komla Folly, (2023) “Mechanical energy storage systems and their applications in power systems,” In *J. Wang and A. Yonesi (Eds), Energy storage applications in power systems*, London, UK, IntechOpen, (June 2023): 1-20. DOI: [10.5772/intechopen.111399](https://doi.org/10.5772/intechopen.111399)

Conference proceedings

7. **Okafor Chukwuemeka Emmanuel** and Komla Folly, “Sizing of Battery Energy Storage System (BESS) for Inertia Response Support,” in **2022 IEEE PES IAS PowerAfrica, Kigali, Rwanda (August 2022)** DOI: [10.1109/PowerAfrica53997.2022.9905309](https://doi.org/10.1109/PowerAfrica53997.2022.9905309)
8. **Okafor Chukwuemeka Emmanuel** and Komla Folly, “Optimal Placement of a Battery Energy Storage System (BESS) in a Distribution Network” in

2023 SAUPEC Conference, Johannesburg, South Africa (January 2023)
DOI: [10.1109/SAUPEC57889.2023.10057659](https://doi.org/10.1109/SAUPEC57889.2023.10057659)

9. **Okafor Chukwuemeka Emmanuel**, Komla Folly, Olasoji Azeez, and David Oyedokun, “Deployment of demand response and battery energy storage system (BESS) for frequency support in a power system with high penetrations of renewable energy sources,” in *2024 IEEE International Conference on Electrical and Computer Engineering Research, (ICECER) Gaborone, Botswana. (presented on 5th December 2024, not yet uploaded to IEEE Explore)*
10. Ayokunle Ayeleso, **Okafor Chukwuemeka Emmanuel**, and Azeez Olasoji, “Investigation of frequency response of a power system network under varying penetrations of renewable energy sources,” in *2024 IEEE International Conference on Electrical and Computer Engineering Research, (ICECER) Gaborone, Botswana, (presented on 5th December 2024, not yet uploaded to IEEE Explore)*
11. **Okafor Chukwuemeka Emmanuel**, Komla Folly, Olasoji Azeez, and David Oyedokun, “Improving power system voltage stability using battery energy storage system (BESS)”, in *2025 IEEE Southern African Universities Power Engineering Conference (SAUPEC), (presented on 29th January 2025, not yet uploaded to IEEE Explore)*
12. Sahed Gbadamosi, **Okafor Chukwuemeka Emmanuel**, Senthil, Krishnamurthy, Ratshanga Mukovhe and Moodley P, “Impact of an electric vehicle. Solar PV and battery energy storage system in a distribution system,” in *2025 IEEE Southern African Universities Power Engineering Conference (SAUPEC), (presented on the 30th January 2025, not yet uploaded to IEEE Explore)*

9. APPENDICES

9.1 The PSO codes

9.1.1 The PSO main codes

%% PARTICLE SWARM OPTIMIZATION (PSO)

```

function [bestfitIter,best_Particle,bestParticle_Position] =
PSO1_test_main(ObjFun,LB,UB,nVar,nPop,MaxIt)
%% Problem Parameters
prob = ObjFun;           % fitness function
Var = nVar;              % number of variables
lb = LB;                 % Variable Lower Bound
ub = UB;                 % Variable Upper Bound
cPop = nPop;              % class population size
Maxiter = MaxIt;         % max no of iteration

%% PSO Parameters
w=0.45;                  % Inertia Weight
c1=1;                    % Personal Learning Coefficient
c2=1;                    % Global Learning Coefficient

%% Starting the Particle Swarm Optimization
f = NaN(cPop,1);         % vector for fitness fun value of the population
D = Var;                 % length of decision variables

bestfitIter = NaN(Maxiter+1,1); % vector to store best fitness fun value per
iteration

P = repmat(lb,cPop,1) + repmat((ub-lb),cPop,1).*rand(cPop,D); % generation
of initial positon of the particles in the population
V = repmat(lb,cPop,1) + repmat((ub-lb),cPop,1).*rand(cPop,D); % generation
of initial velocity of each particle

for q = 1:cPop
    f(q) = prob(P(q,:)); % evaluating the fitness fun value of initial
population
end

bestfitIter(1) = min(f); % vector to store best fitness value of the 0th
iteration

pbest = P;               % initialize the personal best solution
f_pbest = f;             % initialize the fitness of the personal best solution

[f_gbest,ind] = min(f_pbest); % initialize the best objective function value
gbest = P(ind,:);        % dtermine the best solution

%% Iteration Loop (Main Loop)
for t = 1:Maxiter

```

```

for q = 1:cPop
    V(q,:) = w*V(q,:) + c1*rand(1,D).*(pbest(q,:)-P(q,:)) +
c2*rand(1,D).*(gbest - P(q,:));    % Determine the new velocity

    P(q,:) = P(q,:) + V(q,:);    % update the position

    P(q,:) = max(P(q,:),LB);    % bounding the violating to their lower bound
    P(q,:) = min(P(q,:),UB);    % bounding the violating to their upper bound

    f(q) = prob(P(q,:));        % determine the fitness of the new solution

    if f(q) < f_pbest(q)
        f_pbest(q) = f(q);    % update the fitness function value of the personal
best soultion
        pbest(q,:) = P(q,:);    % update the personal best soultion

        if f_pbest(q) < f_gbest
            f_gbest = f_pbest(q);    % update the fitness function value of the
global best soultion
            gbest = pbest(q,:);    % update the global best soultion
        end
    end
end
bestfitIter(t+1) = f_gbest;
end

% Results
best_Particle = f_gbest;
bestParticle_Position = gbest;

```

8.1.2 The PSO Test codes (in MATLAB)

```

clear All; clc; close All
% This main script is to test PSO algorithms
rng(0,'twister') % your result are consistent

%%%%%%%%%%%%% Define your Parameters here
%%%%%%%%%%%%%

%%%%%%%%%%%%% PSO Tuning Parameters %%%%%%%%%%%%%%
Dim=30; Particles = 500; MaxItr = 100 ; run = 10; nVar=1; LB=0.1; UB=1.0;

```

```

% Bound
LB = LB.*ones(1,nVar);      % Lower Bounds
UB = UB.*ones(1,nVar);      % Upper Bounds

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Objective function % Constraint %%%%%%%%%%

ObjFun = F(X);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Main Loop %%%%%%%%%%
for i = 1:run
[Iteration,Best,Position] =
PSO1_test_main(ObjFun,LB,UB,nVar,Particles,MaxItr);
Best_run(i) = Best; %#ok<*SAGROW>
Position_run(i,:) = Position;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Plot Result section %%%%%%%%%%
plot(Iteration)
% print solution
disp('Solution')

```

9.2 The DSO codes (in MATLAB)

9.2.1 The DSO main codes

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% DEEP SLEEP OPTIMIZATION (DSO).
%
% Authors: Stephen Ekwe and Sunday Oladejo
%
% Version: TWO PROCESS MODEL (TPM) APPROACH
%
% Last Update: 2021-10-15 %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Best] = DSO_TPM_v7(ObjFun,LB,UB,dim,search_agent,run)
%% Problem Parameters
prob = ObjFun;      % objective function
nVar = dim;         % dimension of problem
lb = LB;            % lower bound
ub = UB;            % upper bound

```

```

nPop = search_agent;          % no. of search agent
MaxIt = run;                  % no. of individual runs

%% DSO Tuning Parameters
H0_minus = 0.17;             % minimum initial homeostatic value of search
space
H0_plus = 0.85;              % maximum initial homeostatic value of search
space
a = 0.1;                     % circadian cost per unit function
xs = 4.2;                    % sleep power index
xw = 18.2;                   % wake power index
T = 24;                      % maximum sleep duration of agent

%% Pre-allocate
fit = zeros(nPop,1);         % vector to store fitness value
Best.iteration = zeros(MaxIt+1,1); % vector to store best fitness value per
iteration

%% Starting Deep Sleep Optimization
C = sin((2*pi)/T);           % set the periodic function
H_min = H0_minus + a.*C;      % set homeostatic lower threshold
H_max = H0_plus + a.*C;       % set homeostatic upper threshold

Pop = repmat(lb,nPop,1) + repmat((ub-lb),nPop,1).*rand(nPop,nVar); %
generate initial population of search agents

%% Evaluate fitness
for q = 1:nPop
    fit(q) = prob(Pop(q,:));   % evaluating the fitness value of the initial
solution
end
Best.iteration(1) = min(fit);  % stores the best fitness value of the 0th
iteration

%% Main Loop
for i = 1:MaxIt
    for j = 1:nPop
        % Get initial population for 2D plot
        %if (i==1) && (j==round(nPop*0.1))
        %    int_pop.one = Pop;
        %elseif (i==1) && (j==round(nPop*0.5))
        %    int_pop.Fone = Pop;

```

```

%elseif (i==2) && (j==round(nPop*0.1))
%   int_pop.two = Pop;
%elseif (i==3) && (j==round(nPop*0.2))
%   int_pop.three = Pop;
%elseif (i==4) && (j==round(nPop*0.5))
%   int_pop.four = Pop;
%elseif (i==5) && (j==round(nPop*0.8))
%   int_pop.five = Pop;
%elseif (i==MaxIt) && (j==nPop*1)
%   int_pop.last = Pop;
%end

Xini = (Pop(j,:));           % obtain initial solution of agent
[~,ind] = min(fit);         % determine the position of agent with best
fitness
Xbest = Pop(ind,:);         % obtain initial best solution

mu = rand;                  % randomly select asymptote value
mu = min(H_max,mu);         % bound violating asymptote to upper
bound
mu = max(H_min,mu);         % bound violating asymptote to lower
bound

H0 = Pop(j,:) + rand(1,nVar).*(Xbest - mu.*Xini); % obtain candidate
solution

% randomly compute candidate solution based on Sleep-Wake cycle
if (rand > mu)
    H = H0.*10^(-1/xs);      % exploit agent position as homeostatic
pressure decreases during sleep
else
    H = mu + (H0-mu).*10^(-1/xw); % explore other positions as
homeostatic pressure increases during wake
end

H = min(ub,H);              % bound violating variables to their upper bound
H = max(lb,H);              % bound violating variables to their lower bound

fnew = prob(H);             % evaluating the fitness of new candidate solution
if (fnew < fit(j))           % greedy selection
    Pop(j,:) = H;           % include the new solution in population
    fit(j) = fnew;          % include the new fitness to fitness function of
population

```

```

        end
    end
    Best.iteration(i+1) = min(fit); % store best fitness per iteration
end
% DSO-TPM Solution: Global best value and position
[Best.Cost,ind] = min(fit); Best.Position = Pop(ind,:);
End

```

9.2.2 The DSO Test codes (in MATLAB)

```

% Fitness Function
function [z] = myFitn(x)
global matriz

[val,ind]=sort(x);

path=[ind ind(1)];
pathcost=0;
for ik=1:numel(path)-1
    pathcost=pathcost+matriz(path(ik),path(ik+1));
end
%
z=pathcost;

end

```

9.3 The regression analysis codes (in MATLAB)

```

% Sample Data
x = F(x1);
y = F(x2); % Dependent variable];
% Design matrix for third-order polynomial
X = [ones(size(x)), x, x.^2, x.^3];
% Calculate the coefficients
a = (X' * X) \ (X' * y);
% Display the coefficients
disp('Coefficients (a0, a1, a2, a3):');
disp(a');

```

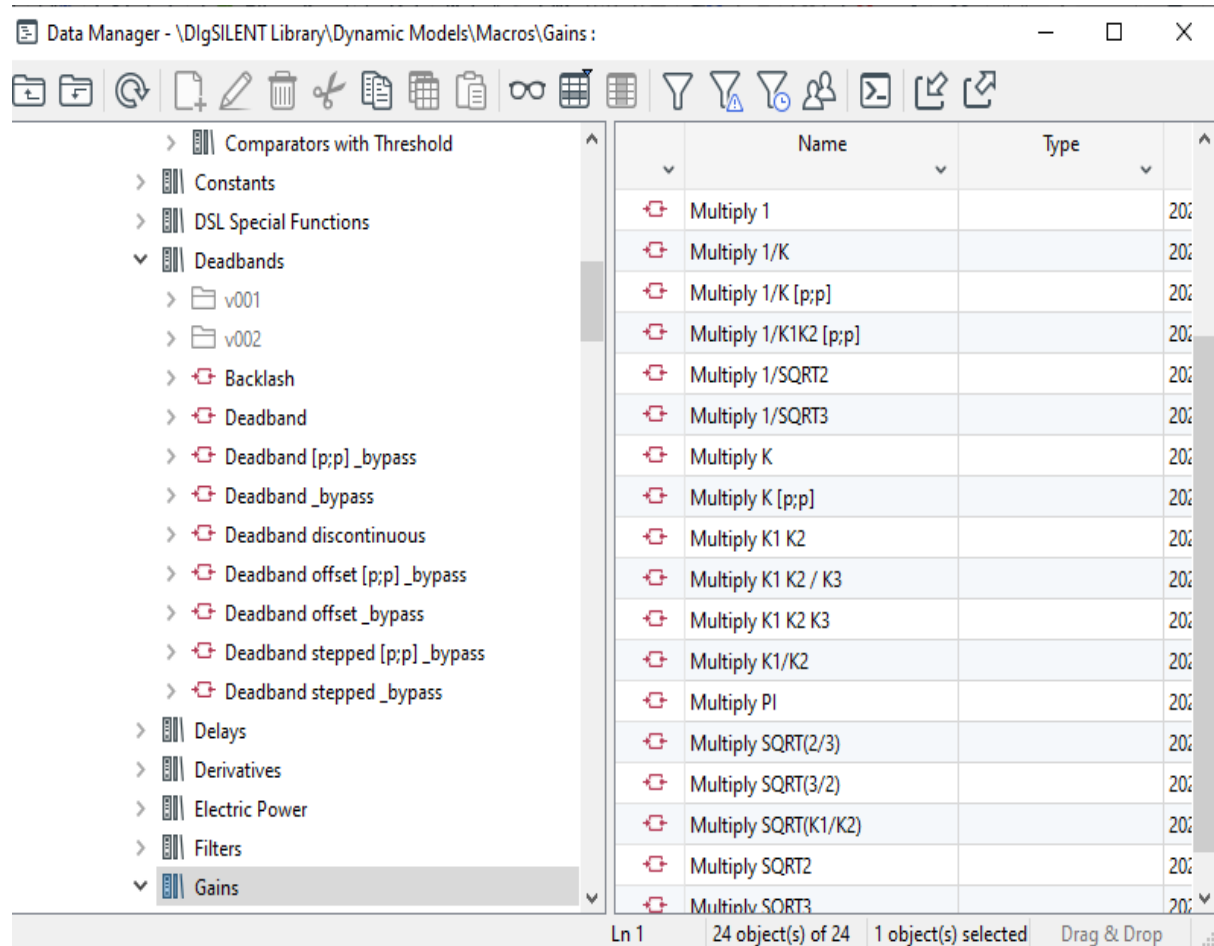
```

% Predict values using the polynomial model
y_pred = X * a;
% Plot the original data and the fitted curve
figure;
scatter(x, y, 'b', 'filled');
hold on;
plot(x, y_pred, 'r', 'LineWidth', 2);
xlabel('x');
ylabel('y');
title('Third-Order Polynomial Regression');
legend('Data', 'Fitted Curve');
grid on;
% Display the regression formula
fprintf('Regression formula: y = %.4f + %.4fx + %.4fx^2 + %.4fx^3\n', a(1),
a(2), a(3), a(4));

```

9.4 Implementation of the BESS control system using DIgSILENT Power Factory (Screenshots)

9.4.1 Some DIgSILENT Power Factory, standard models (macros)



9.4.2 DIgSILENT Power Factory, editing page of block/model definition

The screenshot shows the 'General' tab of a dialog box for defining a block or model. The left sidebar contains a list of tabs: 'Basic Options' (selected), 'Equations', 'Description', and 'Version'. The main area is divided into several sections. At the top, there are tabs for 'General' and 'Advanced'. Below these, the 'Name' field is set to 'InternVoltage' and the 'Usage' is 'Model Definition'. The 'Title' field is empty. The 'Model type' section has three radio buttons: 'DSL model' (selected), 'Compiled model', and 'MATLAB M-file model'. There is also a 'Macro' checkbox which is unchecked. The 'Variables' section contains five input fields: 'Output signals' (u0), 'Input signals' (SOC), 'State variables' (empty), 'Parameters' (u_min, u_max), and 'Internal variables' (empty). The 'Limiting parameters/input signals' section is at the bottom and is divided into two columns: 'Upper limitation' and 'Lower limitation'. Each column has two input fields: 'Parameters' and 'Input signals', both of which are empty. On the right side of the dialog, there is a vertical stack of buttons: 'OK' (highlighted with a blue border), 'Cancel', 'Check', 'Equations', 'Macro equat.', 'Pack', 'Pack->Macro', and 'Encrypt'.

Basic Options

General Advanced

Name: InternVoltage Usage: Model Definition

Title:

Model type

☒ DSL model ☐ Macro

☐ Compiled model

☐ MATLAB M-file model

Variables

Output signals: u0

Input signals: SOC

State variables:

Parameters: u_min, u_max

Internal variables:

Limiting parameters/input signals

Upper limitation

Parameters:

Input signals:

Lower limitation

Parameters:

Input signals:

OK Cancel Check Equations Macro equat. Pack Pack->Macro Encrypt

9.4.3 DIgSILENT Power Factory, mathematical definition page of block/model definition

Basic Options

Equations

Description

Version

Additional equations

```

inc(charging)=0
inc(icharge)=0
inc(startc)=0
inc(endc)=1
inc(breakc)=0
inc(xcharge)=0
!select the charge current
xcharge=(select(charging=1,select(idr>0.5,0,select(idr<-ChargeCur,idr,-ChargeCur)
icharge=xcharge

!charging will be stopped if..
breakc=picdro({SOC>=(maxSOC+minSOC)/2 .and. idr > 0.1},10,0)
endc=picdro({SOC>=(maxSOC-0.2) .or. breakc},0,0)
!charging will be started if..
startc=picdro({SOC<=minSOC .or. {SOC<((maxSOC+minSOC)/2-0.1) .and. idr <=0.01}},5,
charging=flipflop(startc,endc) !Hysteresis output is 1 or 0

!hysteris for power absorption
inc(endload)=0
inc(startload)=1
inc(load)=1
endload=picdro(SOC>=maxSOC,5,0)
startload=picdro(SOC< (maxSOC-0.1),0,0)
load=flipflop(startload,endload)

idref=select(charging,icharge,select(load,idr,lim(idr,0,1.2)))
            
```

<
>

OK

Cancel

Check

Equations

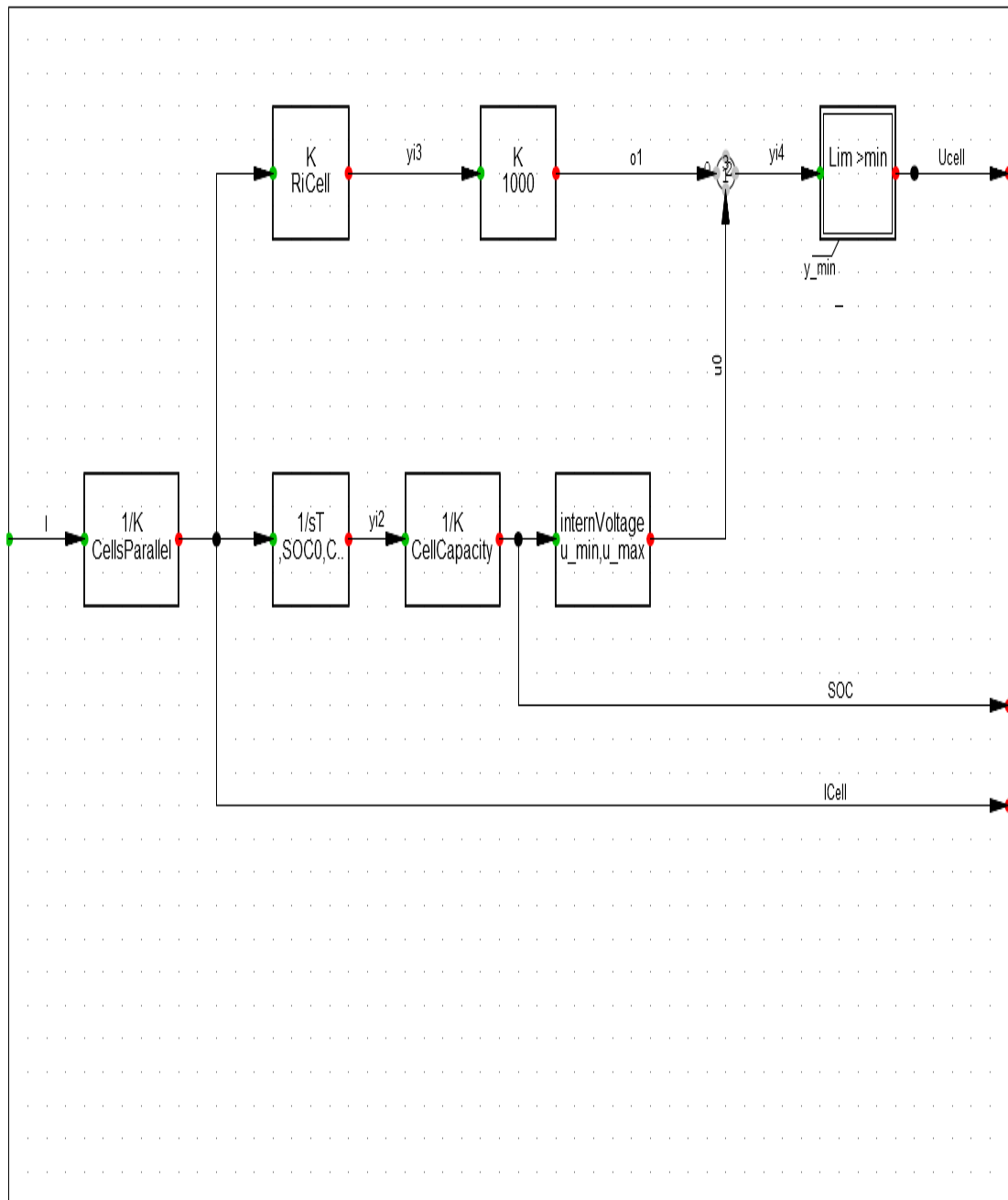
Macro equat.

Pack

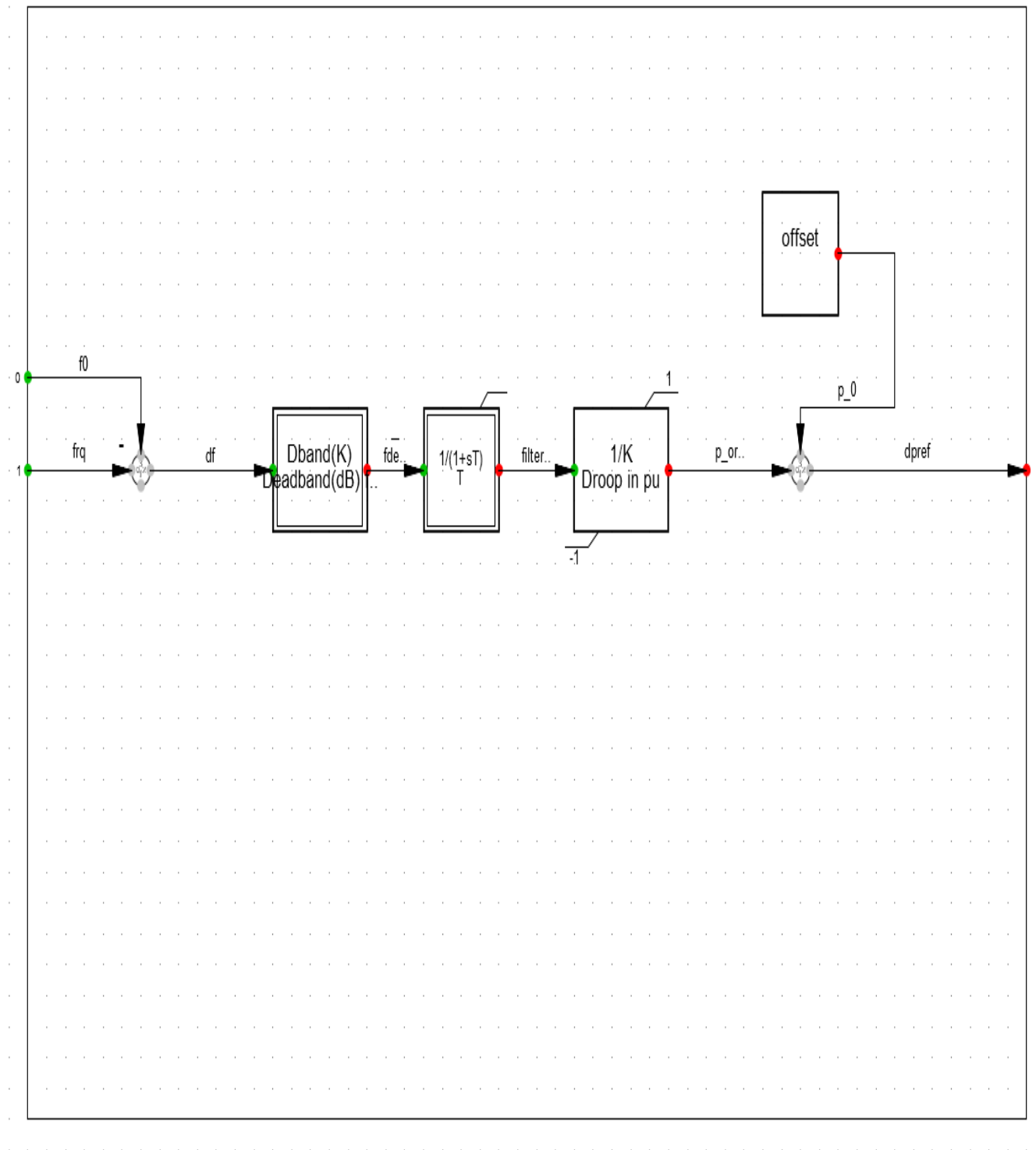
Pack->Macro

Encrypt

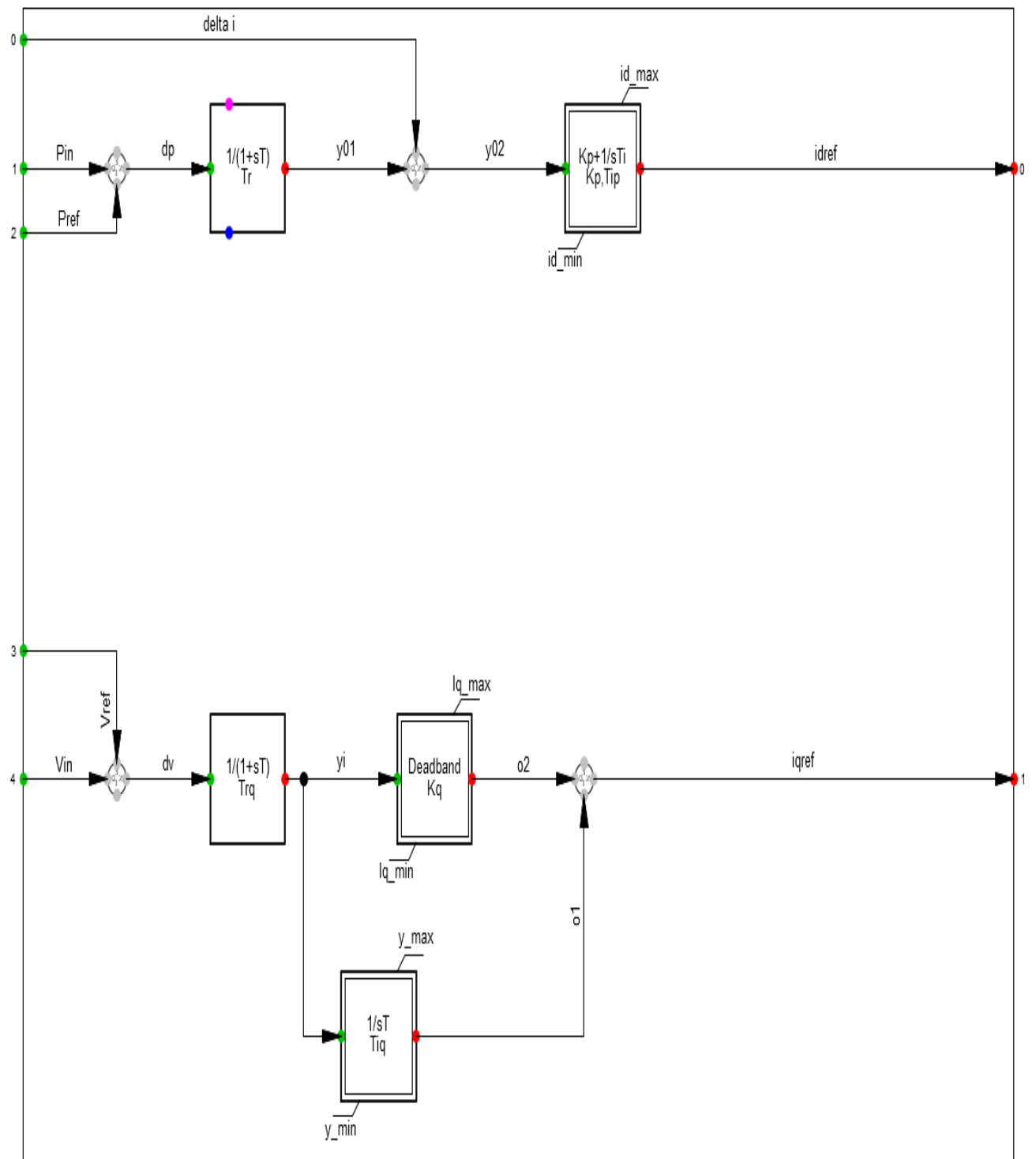
9.4.4 DIgSILENT Power Factory battery block definition.



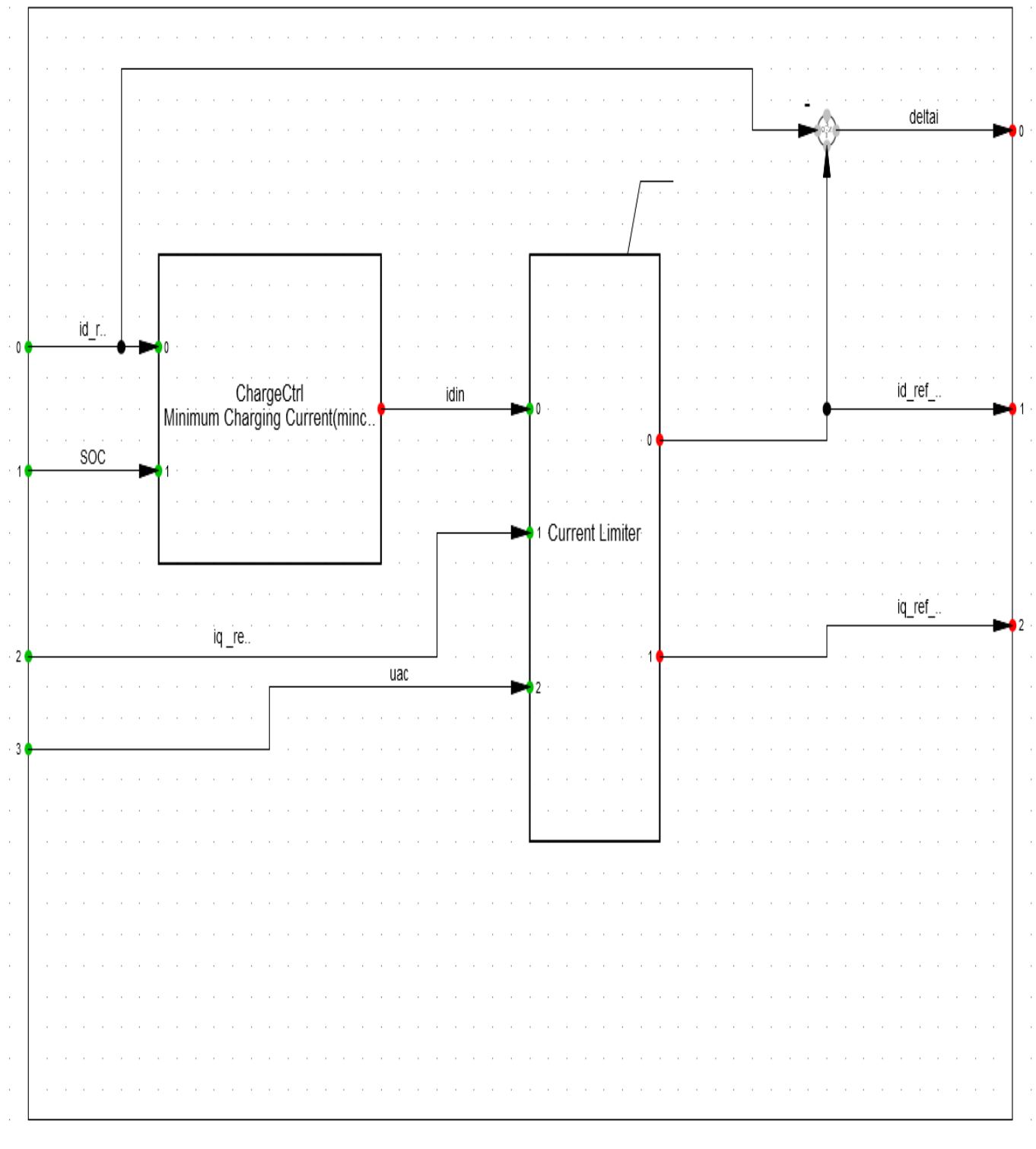
9.4.5 DIgSILENT Power Factory, frequency controller block definition



9.4.6 DIgSILENT Power Factory, PQ controller block definition



9.4.7 DIgSILENT Power Factory, charge controller block definition



9.4.8 DIgSILENT Power Factory, battery common model

dsl Common Model - Battery Common Model.ElmDsl

Basic Data

Description

General Advanced 1 Advanced 2 Advanced 3

Name Battery Common Model

Model Definition ...odels\BATTERY BLOCK DEFINITION

Configuration Script

☐ Out of Service ☒ A-stable integration algorithm

	Parameter	
Cell in parallel	264.	
State of charge at initialization(SOC0)	0.8	
Cellcapacity per cell (Ah)	80.	
Minimum voltage of empty cell (U_min) in (V)	12.	
Maximum voltage of cell (U_max)in (V)	13.85	
Internal resistance of cell (Ricell) in ohms	0.03	
CellinRow	243.	

Export to Clipboard Set to default

OK Cancel Events Arrays/Matrices

9.4.9 DIgSILENT Power Factory, frequency controller common model

Common Model - Frequency Controller Common Model.ElmDsl*

Basic Data

Description

General Advanced 1 Advanced 2 Advanced 3

Name: Frequency Controller Common Model

Model Definition: ...uency Controller Block Definition 2

Configuration Script: →

☐ Out of Service ☒ A-stable integration algorithm

	Parameter
Frequency Droop in pu	0.002
▶ Deadband(dB) for Frequency Control in pu	0.004

Export to Clipboard Set to default

OK Cancel Events Arrays/Matrices

9.4.10 DIgSILENT Power Factory, PQ controller common model

Common Model - PQ Controller Common Model.ElmDsl*

Basic Data

Description

Name: PQ Controller Common Model

Model Definition: ...fined Models\PQ Block definition 2

Configuration Script:

☐ Out of Service ☒ A-stable integration algorithm

	Parameter
Filter Time Constant d-axis in (s) Tr	0.05
Filter time Constant for q-axis in (s) Trq	0.01
Proportional gain d-axis (Kp)	2.
Integration Time constant d-axis in (s)Tip	0.2
AC_deadband for proportional gain (Kdb)	0.1
proportional gain for q-axis Kq	1.
Integrator Time Constant (in s) q-axisTiq	1.
Minimum Current d-axis in pu (id_min)	-1.
Minimum current (pu) q-axis iq_min	-1.
Maximum Current d-axis in pu(id_max)	1.
► Maximum current (pu) q-axisiq_max	1.

Export to Clipboard Set to default

OK Cancel Events Arrays/Matrices

9.4.11 DIgSILENT Power Factory, charge controller common model

dsl Common Model - Charge Controller Common Model.ElmDsl

Basic Data

Description

General Advanced 1 Advanced 2 Advanced 3

Name Charge Controller Common Model

Model Definition [...\Charge Controller Block Definition](#)

Configuration Script

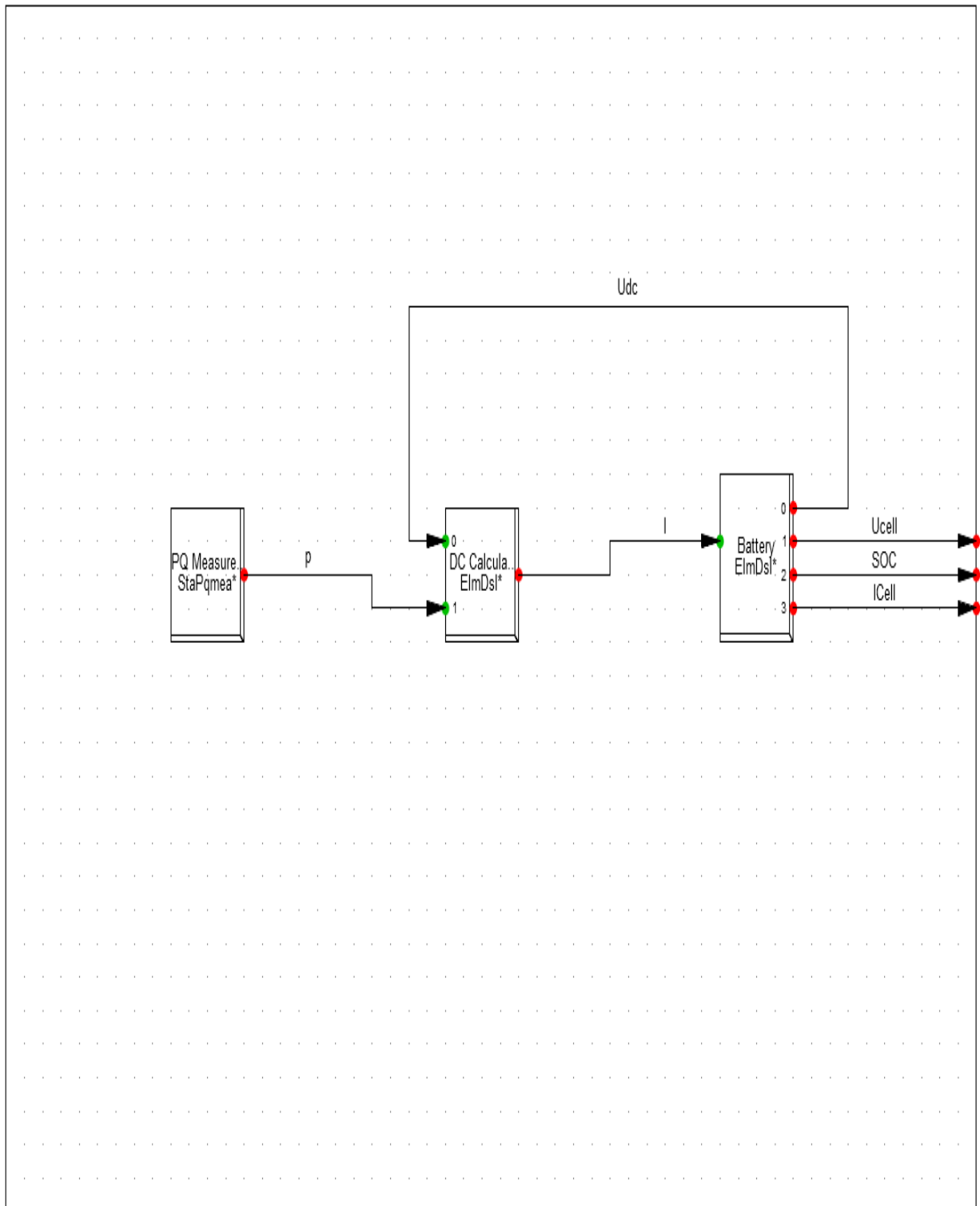
☐ Out of Service ☒ A-stable integration algorithm

	Parameter
Minimum Charging Current(minchargeCur) in pu	0.5
Minimum State of Charge(minSOC) in pu	0.2
Maximum State of Charge(maxSOC) in pu	0.8

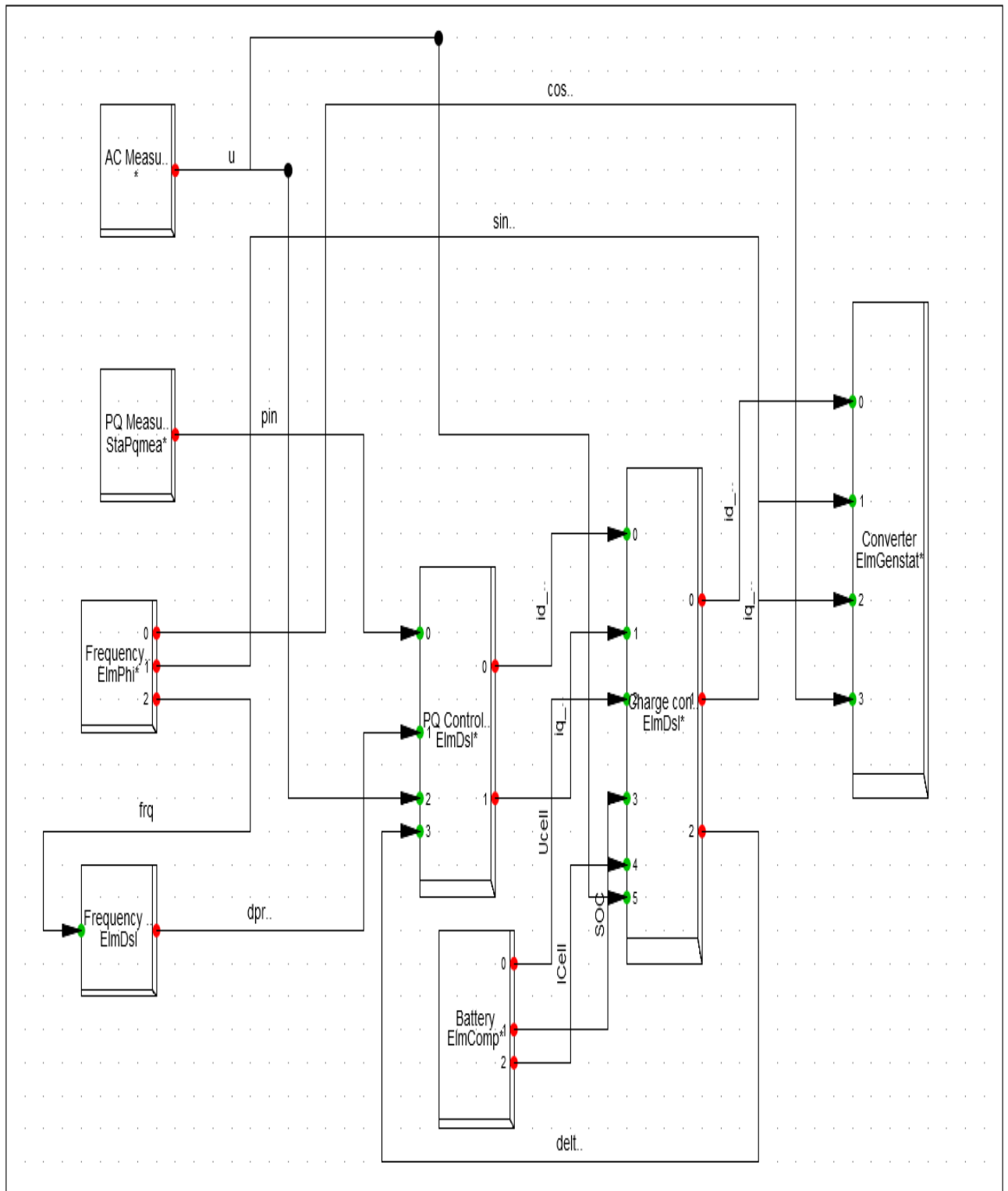
Export to Clipboard Set to default

OK Cancel Events Arrays/Matrices

9.4.12 DIgSILENT Power Factory, battery composite frame



9.4.13 DIgSILENT Power Factory, BESS control composite frame



9.4.14 DIgSILENT Power Factory, BESS control composite model

Composite Model - BESS Control Composite Model.ElmComp

X

Basic Data

Description

Name

BESS Control Composite Model

Frame

▼

→

...els\BESS Control 2 composite frame

☐ Out of Service

Slot Definition:

	Slots BlkSlot	Net Elements Elm*,Sta*,IntRef
1	Frequency Measurement	Phase Measurement Device PLL-Type N...
2	PQ Measurement	PQ Measurement 2
3	AC Measurement	AC Voltage Measurement 2
4	Frequency Controller	Frequency Controller Common Model 2
5	PQ Controller 2	PQ Controller Common Model
6	Charge controller 2	Charge Controller Common Model
7	Converter	Battery Common Model 2
8	Battery	Battery Composite Model 2

Slot Update

Step Response Test

OK

Cancel

Contents