Impact and management of grid-connected Energy Storage systems on the grid

Prepared by:
Francis Mutetwa

Prepared for: Dr David Oyedokun
EEE4022S
Department of Electrical Engineering
University of Cape Town

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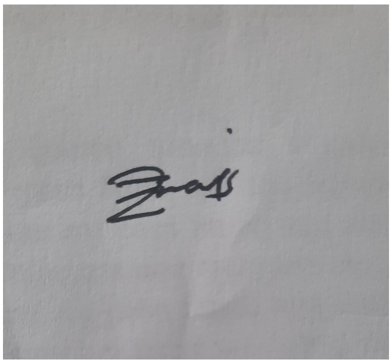

October 25, 2024

Francis Mutetwa

Date

Terms of Reference

The terms of reference have been provided by my supervisor, Dr David Oyedokun and they outline the expectation for this report. The terms of reference are shown below.

Student proposed?	*Y/N*	*If Y, student name*
ID:	**DTO24-02**	
SUPERVISOR:	A/Prof. David Oyedokun	
TITLE:	Impact and management of grid-connected Energy Storage systems on the grid	
DESCRIPTION:	Conventional grid scale energy storage systems have been limited to the primary source of energy- hydro- using pump storage schemes. South runs a few hydro pump storage schemes which includes Palmiet and Steenbras pump storage power stations in the Western Cape. Here is the principle in summary. Electricity is bought during the time of day which it is cheaper (usually at night) pump water in the lower dam up a mountain to the upper dam. When the price of electricity is higher (during the day) water is released through tunnels to generate electricity, making a profit, or meeting demand when needed. The advancement in battery energy storage technologies, especially Lithium based battery cells created an opportunity for electrical energy storage in large scale. Utilities and IPPs around the world are currently considering, and in some cases adopting grid-level implementation of BESS to counter the technical challenges with the intermittency of wind and solar power generation. In this project, the student will study the impact of grid scale BEEE on the stability of the power system and improving the transfer capacity of transmission lines, through a time-based operation.	
DELIVERABLES:	• Project report • Woking model with all relevant files.	

Figure 1: Terms of Reference

Acknowledgements

I would like to thank my supervisor Dr David Oyedokun for all the academic help and support. And I would like to thank Emmanuel Okafor for help with setting up powerfactory software. Special thanks to my parents for encouraging me and supporting me financially throughout this journey and my siblings for always checking to see if I am making progress and supporting me. Lastly, I want to thank God for guiding me throughout.

Abstract

Renewable energy has experienced considerable growth in recent years, with increasing integration of wind and solar sources due to the advantages of clean energy generation. However, despite these benefits, the intermittency of wind and solar generation introduces power fluctuation challenges. Additionally, maintaining power grids with a high share of converter-based renewable energy is complex, presenting significant challenges for power system operators. Another issue with renewables, such as photovoltaics (PV), is their low inertial support, which can lead to grid stability issues and potential blackouts. Battery Energy Storage Systems (BESS) are expected to play a critical role in addressing these stability issues associated with renewable integration.

This project outlines a methodology to investigate the impact of BESS on power system stability and examines how the transfer capacity of transmission lines can be enhanced by incorporating BESS into the grid. Results from frequency stability analysis indicated that BESS can provide synthetic inertial support after a system contingency event, such as a sudden load increase. We also observed that BESS size influences transfer capacity and frequency response following a contingency. Voltage stability index (VSI) calculations before and after BESS implementation showed an improvement in the FVSI value, demonstrating enhanced voltage stability. Lastly it was observed that BESS can improve power transfer across transmission lines by smoothing power fluctuations. From these findings, a theoretical formulation of the relationship between solar irradiation, power transfer capacity, time of day, size of BESS and PV penetration was formulated.

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Chapter 1

Introduction

1.1 Background to the study

In recent years, significant improvements have been made in the field of battery energy storage systems, leading utilities worldwide to consider replacing conventional energy storage methods such as pump storage schemes. Researchers are motivated to explore how the implementation of battery energy storage systems on a large scale would impact the grid. The growing adoption of renewables like wind and solar has further fueled the interest in these battery energy storage systems due to the technical problems that come along with implementing them on the grid.

The integration of renewables such as solar and wind into the grid presents several challenges, including frequency stability and voltage stability issues. Previous research has demonstrated that large-scale implementation of battery energy storage systems can enhance grid stability and mitigate the challenges posed by renewables. This research project explores the concepts of battery storage integration on grid stability.

1.2 Project Objectives

This thesis examines the impact of Battery Energy Storage Systems (BESS) on grid stability and their role in enhancing the transfer capacity of transmission lines through time-based operation. It explores concepts that will help formulate the relationship between solar irradiance, power transfer capacity, time of day, size of BESS, and PV penetration

1.2.1 Hypothesis

Battery Energy Storage Systems improve voltage and frequency stability on the grid and it helps improve the transfer capacity of transmission lines

1.2.2 Research Questions

1. How does a battery energy storage system offer voltage support to the grid?
2. In what ways does the storage system provide frequency support?
3. How do these systems enhance the steady state and transient stability for high levels of PV penetration within the grid?

4. What is the relationship between solar irradiation, power transfer capacity, time of day, size of BESS, and PV penetration?

1.3 Scope and Limitations

This project will investigate how battery energy storage systems enhance grid stability. The investigation will be conducted using a power system model simulated in DIgSILENT PowerFactory to observe how the energy storage system strengthens the power grid frequency and voltage stability. The renewable energy studied will be limited to solar power to determine the relationship between solar irradiation, power transfer capacity, time of day, size of BESS, and PV penetration. The solar irradiance data will be collected for the Northen Cape South Africa.

1.4 Plan of Development

1.4.1 Introduction

This chapter initiates the report by outlining the background of the project's development and its objectives. It also emphasizes the research questions, hypothesis, scope, limitations, and the development plan.

1.4.2 Literature Review

This chapter reviews existing research on grid energy storage systems and their effects on grid stability. It then focuses specifically on Battery Energy Storage Systems (BESS) used in conjunction with renewable sources such as wind and solar power. Additionally, it examines how these renewable sources impact grid stability and how BESS can help mitigate these effects.

1.4.3 Methodology and Design

In this section the methodology chapter is outlined and it defines the approach for conducting the study and provides justifications for the design choices in the power system simulation. It details the design parameters used for various simulation models and outlines the overall power system design and the area under focus in the power system.

1.4.4 Results and Discussion

In this section, we record the results and analyze them to see if they align with our proposed hypothesis.

1.4.5 Conclusion

This section will determine whether the hypothesis has been validated based on the results obtained in the previous chapter.

Chapter 2

Literature Review

The literature review for this project addresses the topics outlined in the research questions in section 1.2.2, offering a comprehensive assessment of existing research, solutions, and applications relevant to the project. It draws on technical reports, prior research, and studies from experts specializing in renewable energy and energy storage systems. The review begins with an overview of grid scale energy storage systems inorder to establish a foundational understanding of the different energy storage systems available and the services they offer.

2.1 Introduction to grid scale energy storage systems

2.1.1 Overview of Energy Storage Systems

There are various forms of energy storage systems that have been implemented over the last couple of years. In this section of this literature review, we discuss the different types of energy storage systems and compare mechanical, thermal and electrochemical energy storage systems. We also briefly describe the different types of services the grid connected energy storage systems provide to the grid.

Grid scale energy storage systems have been implemented due to the services they provide to modern power systems. These include bulk energy services such as electricity energy time shift (energy arbitrage), and electricity supply capacity[1, 2]. They also provide ancillary services that include regulation, voltage support, black start and supplementary reserves[1, 2]. The shift to renewable energy has resulted in some problems being introduced to the grid and to counter these problems, energy storage schemes can be used.

Storing electrical energy would involve converting electrical energy into another form [2] and in [1], Farivar et al categorized these various forms of energy storage systems as mechanical, thermal, electrochemical, electrical and chemical. The most common energy storage system would be hydro using pumped storage schemes, categorized under mechanical energy storage systems [1]. With pumped hydro storage schemes, water is pumped back to an elevated position or storage dam, and this is usually done during the time of day when electricity is cheaper which is at night. When the price of electricity is high, water is released to generate electricity. This service is known as energy arbitrage. The principle of peak shaving is the same as that for energy arbitrage except that with peak shaving there is no economic objective. In South Africa, an example of pumped hydro energy storage schemes is Palmiet[1]. Despite pumped hydro storage schemes being able to last for long periods and their widespread use and adoption, they have the limitation of long startups that can be 10 to 15 minutes long, also they are ‘site specific, require large capital to setup, they take a long time to construct and lastly they come with problems related to conservation of ecosystems and wildlife' [2, 3].

Flywheel energy storage system is an alternative mechanical energy storage system with less environmental impacts compared to the pumped hydro storage scheme [4] and it also has faster response times of up to 1 to 100s [2], which is considerably faster than pumped hydro storage schemes. Flywheel energy storage system working principle is 'angular momentum of flywheel is used to store the power in the form of kinetic energy'[2] . The technology is relatively still new capable of storing high power density and energy density, and an infinite number of charging cycles. Their main use is mainly to stabilize voltage and frequency. Despite FESS requiring lower maintenance, being less prone to temperature fluctuations and having the ability to discharge within few minutes[2], they are quite expensive to setup given that they are still a relatively new technology and it still requires a lot of research and development before it fully matures, hence it has not seen much widespread adoption[2].

The focus of this literature review will be on electrical energy storage schemes, particularly lithium-ion battery energy storage schemes.

2.1.2 BESS in the Context of Renewable Energy

Renewable energy such as PV and wind have been widely adopted over the last couple of decades. Power grids are transitioning from synchronous generation to an increasing reliance on power electronics converter-based electricity generation, both in terms of quantity and rated capacity, connected to the electricity network. Maintaining the stability of power grids with a high share of power electronic converters presents a significant challenge that many power system operators will face and seek to overcome in the near future. Battery Energy Storage Systems (BESSs) are anticipated to play a key role in addressing this issue[1].

The shift to solar energy has been observed to lead to issues such as overvoltage[5]. Imaarim et al [5] mentions that the cause of this was mainly due to static var compensators that then resulted in higher transient overvoltages. It was mentioned that the main reason was the 'injection of reactive power into the system by the SVC's for several cycles due to their low operating speed after clearance of the fault'[5].

2.2 Grid Stability

Kundur et al defined power system stability as "the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact."[6] Power system stability can be done studied as resonance stability, converter driven stability, rotor angle stability, voltage stability and frequency stability according to [6]. This literature review will discuss voltage stability and frequency stability on the grid and how introduction of BESS influences the stability of the grid. The figure 2.1 below illustrates the ways in which grid stability can be studied.

2.2.1 Voltage stability

Kundur et al defined voltage stability as "the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condion."[6]

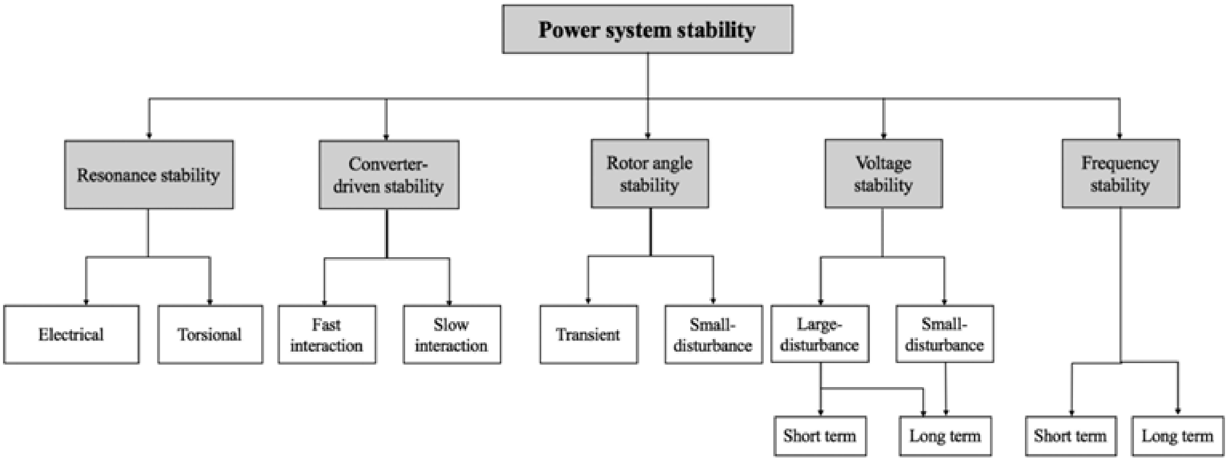

Figure 2.1: Classification of power system stability; Image credit:[6]

Voltage stability relies on the power system's ability to keep supply and demand in equilibrium. If this balance is lost, instability can occur, leading to a steady decline or rise in voltage at specific buses. Voltage stability is compromised when a disturbance causes the demand for reactive power to exceed the capacity of the available reactive power resources. [6]. Reactive power demand is increasing due to an increase in the shift to renewables given that renewables such as PV systems do not inject a lot of reactive power to the grid. The lack of reactive power in the grid often leads to voltage instability and to prevent this ESS's such as BESS can be implemented to compensate for that. It can do this by injecting and absorbing reactive power into or from the grid inorde to keep the nominal voltage level hence ensuring the grid stability and the functionality of equipment[7]. The effects of voltage instability could result in blackouts. Salama et al [8] mentions how in a study conducted by [9], it was observed that most of the blackouts that occurred between 1965 and 2015 were due to voltage instability. Because of this we observe how it is crucial to make sure voltage levels are maintained at the required levels.

Voltage stability involves maintaining steady state voltage levels during disturbances, faults and sudden load changes. [10] defines voltage stability as 'the ability of a power system to transfer active power to the loads keeping the voltages at each bus at acceptable levels.' Voltage support is one way that can be used to ensure that voltage stability is achieved. Different devices can be employed for voltage support, and these include FACTS devices, Battery Energy Storage Systems, synchronous generators, capacitors. Voltage support in high voltage transmission grids involves maintaining voltage levels within acceptable ranges, often through reactive power injection. In [1], there is a discussion on how ESS's can be used as distributed reactive power sources or sinks and this contributes to the voltage levels regulation through the nodes of the transmission and distribution network.

How BESS offers voltage support

[11] observed that there is an improvement in the voltage stability when BESS is introduced. It was seen that 'implementing BESS integrated with Solar PV to a distribution network improved busbar voltage stability'. Mentions that BESS can improve voltage stability in power grids by providing controllable real and reactive power compensation. The PQ Controller or the PV-Control in BESS is

responsible for active and reactive power control of the BESS. The figure 2.2 shown illustrates the block diagram for the PQ controllers responsible for active and reactive power control. The control parameters for the PQ controller can be modified according to the requirements of the application needed.

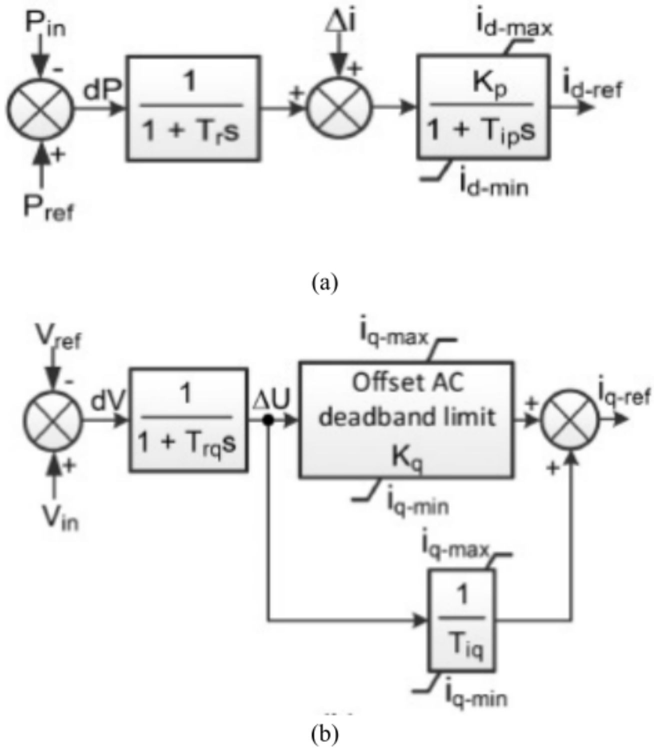

Figure 2.2: PQ Controllers for the real and reactive power; Image credit:[12]

The key parameters that are important in active power control are the Kp(Proportional Gain) and the Tip(Integrator Time Constant) parameters. Tuning these parameters is important to prevent instability.Kp (Proportional Gain) controls the reaction of the controller to the current error (difference between the desired and actual system frequency). A higher Kp results in a faster response, but if Kp is too large, it can cause system instability or oscillations [13]. Tip (Integrator Time Constant) controls how the controller responds to accumulated errors over time. A larger Tip means slower integration, causing the controller to take longer to correct errors. If Tip is too small, it may cause overshooting and oscillations. [13].

Analysing Voltage Stability

There are different ways to study the voltage stability of a power system and these include PV and QV curve analysis, use of voltage stability indices (VSI's) and other methods mentioned in literature. The literature review only discusses VSI's and PV Curves.

Voltage stability can be studied or analysed by different voltage stability indices (VSI's). Voltage stability indicies are essentially numerical indicators that help identify how a power system is close to voltage collapse or instability. VSI's provide a quantitative measurement of the voltage stability in a power system. [8, 14] do a comprehensive review of voltage stability indices that can be used to analyse voltage stability of a power system. For this literature review, comparisons will be done among

6 indices although there are more than 6 indicies available in literature. The table below outlines comparisons of 6 VSI's.

Table 2.1: Comparison of Voltage Stability Indices [14, 8]

Index	Formula	Computational Complexity	Advantages	Disadvantages
FVSI (Fast Voltage Stability Index)	$\text{FVSI} = \frac{4Z_{ij}^2 Q_j}{V_i^2 X_{ij}}$	Low	Quick calculation, good for real-time analysis	Less accurate for complex systems
Lmn	$\text{Lmn} = \frac{4Q_j Z_{ij}}{V_i^2 X_{ij}}$	Low	Simple computation	Similar limitations as FVSI
L-index	$\text{L} = \sum \left(\frac{V_j^2 - V_i^2}{V_i^2} \right) Q_j$	Medium	Provides more detailed system stability info	Requires more data, computationally intensive
Voltage Collapse Proximity Indicator (VCPI)	Depends on system state and parameters	Medium to High	Good for assessing risk of voltage collapse	Complex calculations and requires full system data
T-index	$T = \frac{1}{n} \sum_{i=1}^{n} V_i$	Low to Medium	Oversimplification can overlook critical issues	Complexity can mask important factors
VSI based on Jacobian Matrix	Varies based on system Jacobian	High	Highly accurate, considers system dynamics	Computationally intensive, requires full matrix

Ideally an accurate and low computational complexity VSI should be chosen to ensure that running time of the optimization problem especially in large power systems does not take too long [14].

Voltage stability can also be studied by analysing PV-curves and QV-curves in a power system [15].

Figure 2.3 illustrates a common variation of bus voltage in relation to active load, commonly referred to as a PV-curve (or nose curve) [10].

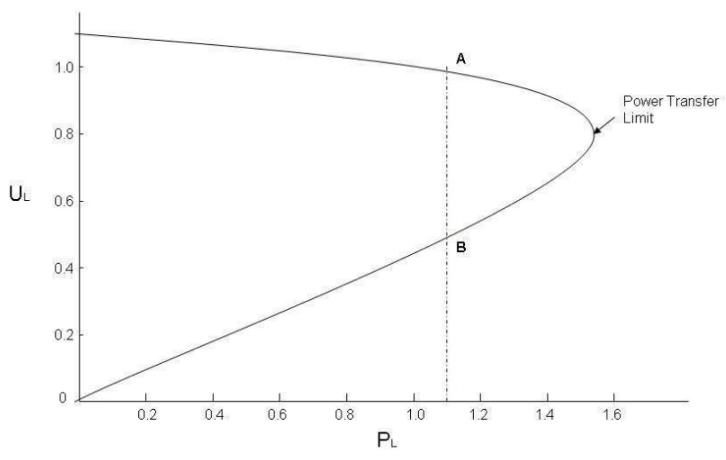

Figure 2.3: PV Curve analysis; Image credit:[10]

Where P_L: The active power load at a specific bus in the power system.

U_L: The voltage level at a specific bus in the power system.

$P_{L,\mathbf{max}}$: The maximum active power that can be consumed from each bus without causing voltage instability. $P_{L,\max}$ defines the voltage transfer limit, beyond which the system is subjected to voltage collapse.

In the graph shown in 2.3, we observe that there are two voltage values that can be read from it for each level of power transfer. The higher voltage A is known as a stable operating and B is accompanied by higher currents and thus higher losses [10]

By combining VSI's, PV and QV curves, valuable insights on the voltage stability of the power system can be obtained and we can observe how BESS can help with voltage support to the grid thus increasing the robustness of the grid.

2.2.2 Frequency Stability

According to [6], frequency stability refers to "the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load". Key metrics for frequency stability analysis include the frequency nadir and the ROCOF (Rate of change of frequency). The nadir is the lowest deep in system frequency before it begins to recover after a disturbance or system contingency occurs such as sudden increase in the load.

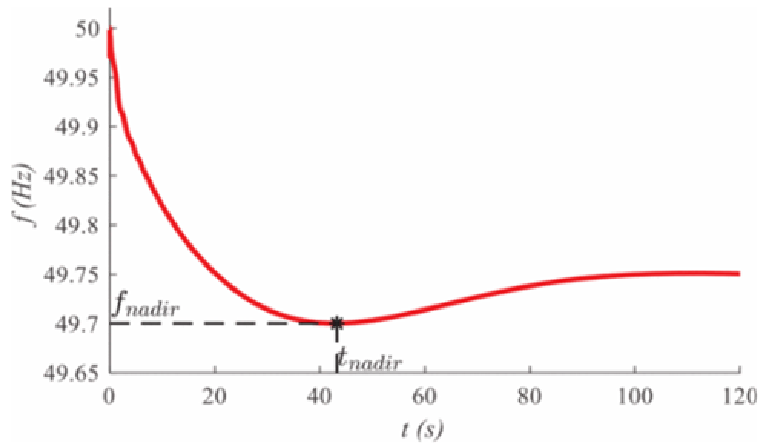

Figure 2.4: Frequency Nadir illustration; Image credit:[6]

Renewable sources such as wind and PV, which are connected by power electronic inverters, do not naturally provide inertia, unlike traditional synchronous generators. The lack of inertia can lead to frequency instability, characterized by a high Rate of Change of Frequency (RoCoF) during power disturbances[12]. The power system frequency is always changing due to varying load demand and the produced electricity. When there is a disturbance in the power system such as a sudden increase in load demand, 'the system frequency will respond at a rate initially determined by the total system inertia.'[12]

To address this, BESS can be equipped with frequency controllers capable of providing what is known as synthetic inertia. [12] defines synthetic inertia as "the ability of non-synchronous generation sources, like Battery Energy Storage Systems (BESS), to emulate the natural inertia provided by synchronous generators.” The figure 2.5 below shows a block diagram of a frequency controller.

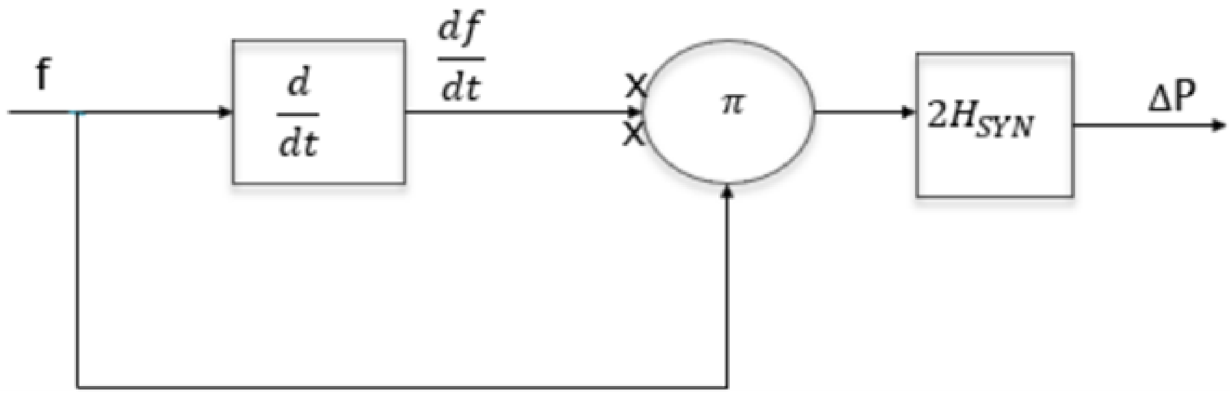

Figure 2.5: Block diagram of the frequency controller[12]

After a contingency event like a sudden increase in the load demand, there is a drop in frequency that will be observed, caused by the imbalance between supply and demand. In [12], there is a discussion on how the inertia controller acts to restore the system to its inital state. The inertia controller is responsible for making sure that active output power is amplified in the event of such an even like a drop in the frequency. When this happens the ‘inertial controller can discharge active power in a controllerd manner’[12] and the swing equation below illustrates this:

$$\Delta P = 2fH_{\mathrm{SYN}}\frac{df}{dt} \tag{2.1}$$

‘where ΔP represents the load generation imbalance in megawatts (MW), f is the system frequency in hertz (Hz), $\frac{df}{dt}$ is the rate of change of frequency (ROCOF) in hertz per second (Hz/s), and H_{SYN} is the synthetic inertia in seconds. The equation defines how frequency changes over time in response to power imbalances’ [12].

The frequency controller block diagram for the Battery Energy Storage System (BESS) is illustrated in Fig 2.5. It consists of the frequency control system, which includes the frequency droop mechanism. The frequency control is based on the rate of change of frequency (RoCoF) [12]. The droop coefficient is determined by the following equation:

$$R_{\mathrm{droop}} = \frac{1}{K_{\mathrm{droop}}} = \frac{\Delta f}{\Delta p} \tag{13}$$

Here, Δp represents ‘the active power variation of the battery, and it is influenced by R_{droop}, where K_{droop} is the droop constant, and Δf is the frequency deviation. The output of the frequency droop/RoCoF control loop provides an active power change signal to the PQ controller’ [12]. In the case of under-frequency conditions, the active power change will be positive, triggering the BESS to discharge. Conversely, in over-frequency conditions, the active power change will be negative, causing the BESS to charge[12]. The relation between active power change and RoCoF is given by the following equation:

$$\Delta p = K_{\text{rocof}} \frac{df}{dt} \tag{14}$$

where K_{rocof} represents the slope of the frequency response.

2.3 Congestion Relief in Transmission Lines

2.3.1 Transfer Capacity of Transmission Lines

Sookananta et al. defines transfer capacity as the maximum power that can be transferred over transmission lines while maintaining system stability and reliability i.e avoiding voltage and thermal limits. [16].

The main indices for tranfer capacity which are Total Transfer Capability(TTC) and Available transfer Capabaility(ATC) [16]. The total transfer capability refers to the maximum amount of electrical power that can be transmitted across the interconnected transmission network while maintaining reliability [16].

A table detailing different calculation methods that can be applied to analyse power transfer capability of a power system is shown in 2.2.

Method	**Description**	**Advantages**	**Disadvantages**
Linear Sensitivity (DC-PTDF)	Uses a DC power transfer distribution factor with a linear model assuming no transmission losses.	Fast computation, simple method, useful in the planning phase.	Low accuracy, neglects losses, does not consider voltage stability.
Linear Sensitivity (AC-DF)	Uses AC power transfer distribution factors that account for both real power flow (AC-PTDF) and voltage effects (VDF).	More accurate than DC-PTDF, includes voltage stability consideration.	Still an approximation, less accurate than other methods such as RPF.
Repeated Power Flow (RPF)	Incrementally increases demand and generation to simulate power flow, repeatedly solving the system until a limit is reached.	Accurate, suitable for detailed analysis.	Computationally expensive, time-consuming for large systems.
Continuation Power Flow (CPF)	Traces the power-voltage (PV) curve to find the point of voltage collapse as system demand increases.	Useful for voltage stability analysis, accurate in systems with voltage stability issues.	Ignores thermal limits unless explicitly included, complex to implement.

Table 2.2: Comparison of methods for calculating transfer capacity. [16]

2.3.2 How BESS Enhances Transfer Capacity

BESS can be programmed to strategically operate during certain times of day when there are peak load demand from consumers on the grid inorder to reduce stress on the transmission network. It can do this by storing excess power generated during off-peak hours and discharging during peak hours, resulting in smoother power flows and congestion is avoided. This results in an increase in tranfer capacity of transmission lines.

2.3.3 Solar Irradiation and Power Transfer

Solar irradiation varies with the time of day resulting in power generated from PV varying. Perfomance of a PV system highly depends on solar irradiance [17]. Varying weather conditions and cloud cover results in varying solar irradiation and hence varying power output thus resulting in fluctuating voltage and flicker. Intermittent nature of PV results in grid instability [17]

2.4 Insights gained from literature review

The literature review effectively introduced the challenges associated with high renewable energy penetration and explored potential solutions, including the use of energy storage systems. It provided insights into various types of energy storage options available and covered essential services offered by BESS, such as energy arbitrage and peak shaving. Additionally, the literature on BESS's role in providing voltage and frequency support to the grid will inform the methodology and discussion sections. Different approaches for analyzing grid stability, like PV and QV curve analysis, will also contribute significantly to the development of the study's methodology.

Chapter 3

Methodology and experimental design

The objective of this project looked to study the impact and management of grid scale BESS implementation on the grid stability and to study how it improves the transfer capacity of transmission lines. The aim is to establish a relationship between solar irradiance, power transfer capacity, time of day, size of BESS and PV penetration in a grid connected power system. In this study, there is particular focus on the transient and steady state stability of the power system when BESS is introduced.

A 21-bus power system model will be used to simulate and a DIgSILENT BESS FrequencyCtrl 10kV 30MVA template model of the Battery Energy Storage system will be used to model the BESS. The BESS Model could not be designed from scratch due to time constraints hence the the decision to use the DIgSilenet BESS template. The models will be simulated in DIgSilent Powerfactory software to assess the impact of battery energy storage systems on the stability of the grid. This study will also include doing steady state and transient state analysis to find the relationship between solar irradiation, power transfer capacity, BESS size, and PV penetration.

3.1 Data Collection

Solar irradiation data was collected for typical different times of day such as morning, afternoon and evening for the Northern Cape Region in South Africa. The data is provided by an online database called PVGIS (Photovoltaic Geographical Information System). The solar irradiation data was provided in .csv format and excel was used to do analysis of the data. The solar irradiation data is attached in the appendix section at the end of the report. Load profile data for the 21 Bus system was also provided for and used in simulations.

3.2 Simulations

Below is an outline of the simulations that will be carried out to investigate the study

1. **EMT analysis (Short Term)**: A transient disturbance (sudden increase in the load demand) will be introduced to the system to observe the effect on the grid frequency stability and to observe how BESS provides synthentic inertial support. This will be done for different cases, such as when there is BESS implementation on the grid and when there is no BESS implementation on the grid. Load variations and BESS sizes will be implemented.

2. **Steady State analysis (Small disturbance)**: The focus will be on observing the impact on voltage stability when small incremental load increases are applied to the loads of the power

system. Load flow and voltage regulation will be studied under stable conditions for both BESS grid implementation and when there is no BESS implementation on the grid.

3. **Quasi-dynamic Simulation**: This will be used to study the time-based behavior of the power system in order to establish a relationship between solar irradiation, power transfer capacity, BESS size, time of day, and PV penetration.

3.2.1 EMT Analysis (Transient Analysis protocol)

Transient analysis protocol will be simulated by introducing a sudden increase in load at key loads of the power system in order to evaluate the short-term frequency stability. The objective of this analysis is to observe how BESS improves the frequency stability of the grid after a contingency such as a sudden increase in the load demand. We aim to observe how BESS can provide synthetic inertial support to the power system in the event of a power system contingency event. Test cases that will be simulated are as follows:

1. Conducting the EMT analysis for the baseline scenario across different power system contingencies of a sudden load increase (10%, 20%, 30%, and 50%)
2. Performing EMT analysis on the baseline case with BESS integration under various power system contingencies, specifically considering sudden load increases (10%, 20%, 30%, and 50%).
3. Conducting EMT analysis on the baseline case, incorporating BESS integration with varied BESS capacities.(30MVA, 90MVA, 100MVA) while keeping the system contingency of a sudden load increase constant at a sudden load increase of 50%.

The following parameters will be plotted over time to illustrate the impact of different PV penetration levels, both with and without BESS integration:

- Electrical Frequency
- Active Power of BESS

The key metric that will be used for analysis is the frequency nadir.

3.2.2 Steady-State Analysis Protocol

The voltage stability analysis will be carried out using the Fast Voltage Stability Index (FVSI) to evaluate the system's ability to maintain voltage stability under varying levels of load increase. The objective of this analysis is to identify weak lines in the power system and determine how BESS can enhance voltage stability. The formula for the FVSI shown below will be applied [8].

$$\text{FVSI} = \frac{4Z^2 Q_r}{V_s^2 X} \tag{3.1}$$

where:

- Z is the line impedance,

- Q_r is the reactive power at the receiving end,
- V_s is the sending bus voltage, and
- X is the line reactance.

the test cases are:

1. Running a load flow and then calculating the FVSI for the base case.
2. Running a load flow and then calculating the FVSI for the base case with BESS integration to observe the improvement in voltage stability.
3. Running a load flow and then calculating FVSI for the base case with varying BESS capacities (30MVA, 90MVA, 100MVA)

The following parameters will be analyzed across different test cases to assess the impact of load increase and BESS integration on voltage stability:

- FVSI value for transmission line NW-Central 400Kv
- Q_r is the reactive power at the receiving end,
- V_s is the sending bus voltage, and

The key metric used for analysis will be the FVSI threshold. A FVSI value greater than 1 indicates potential voltage instability and possible voltage collapse, requiring countermeasures such BESS enhancement. The FVSI was chosen because of its low computational complexity. For manual calculations it would mean quick calcutions. However it would be a the expense of accuracy[8]. Initially, the plan was to write a script to automate the process of finding critically loaded buses and weak lines and then automating the calculation of the FVSI. Due to time constraints this was not possible for this project. The choice to use VSI's for voltage stability analysis was made because of the license restrictions on DIgSilent powerfactory. Inorder to plot PV curves and QV curves, transmission network tools functionality is required, however since I did not have access to these tools I could not plot the PV and QV curves, hence the decision to use voltage stability indices VSI.

3.2.3 Quasi-Dynamic Simulation Protocol

The simulation aims to capture the behavior of the power system under varying time-of-day conditions. Solar irradiance, which varies with weather conditions and time of day, will be used to simulate PV generation intermittency. Solar irradiance varies based on different times of the day (morning, afternoon, and evening). Loads will also be simulated to vary hourly during the day based on consumer usage as the hourly time of day changes. The objective is to analyze how BESS enhances the power transfer capacity of transmission lines by reducing congestion in transmission lines.

The test cases are:

1. Running the Quasi-Dynamic simulation for the base case and varying the PV penetration levels (10%, 20%, 30%, 50%). In PowerFactory, PV penetration will be varied by adjusting the scaling factor, whilst keeping the BESS capacity constant at 60MVA.

2. Running the Quasi-Dynamic simulation analysis for the base case with BESS integration and varying PV penetration levels (10%, 20%, 30%), whilst keeping the BESS capacity constant at 60MVA.

3. Running the Quasi-Dynamic simulation for the base case with BESS integration modified with different BESS capacities (50MVA, 100MVA, 180MVA), whilst keeping the PV penetration constant at 30%.

The active power being transmitted in transmission line NW-Central will be monitored and plotted over a 24-hour period. This will be done with and without BESS integration for comparison.

Ideally, to analyze the power transfer capacity of transmission lines, DIgSILENT PowerFactory's transmission network analysis tools would be used for transfer capacity analysis. However, due to license restrictions, this method cannot be employed in this project.

3.3 Design

The following section presents the system models described in use for simulations as described in the previous chapter.

3.3.1 Base Case

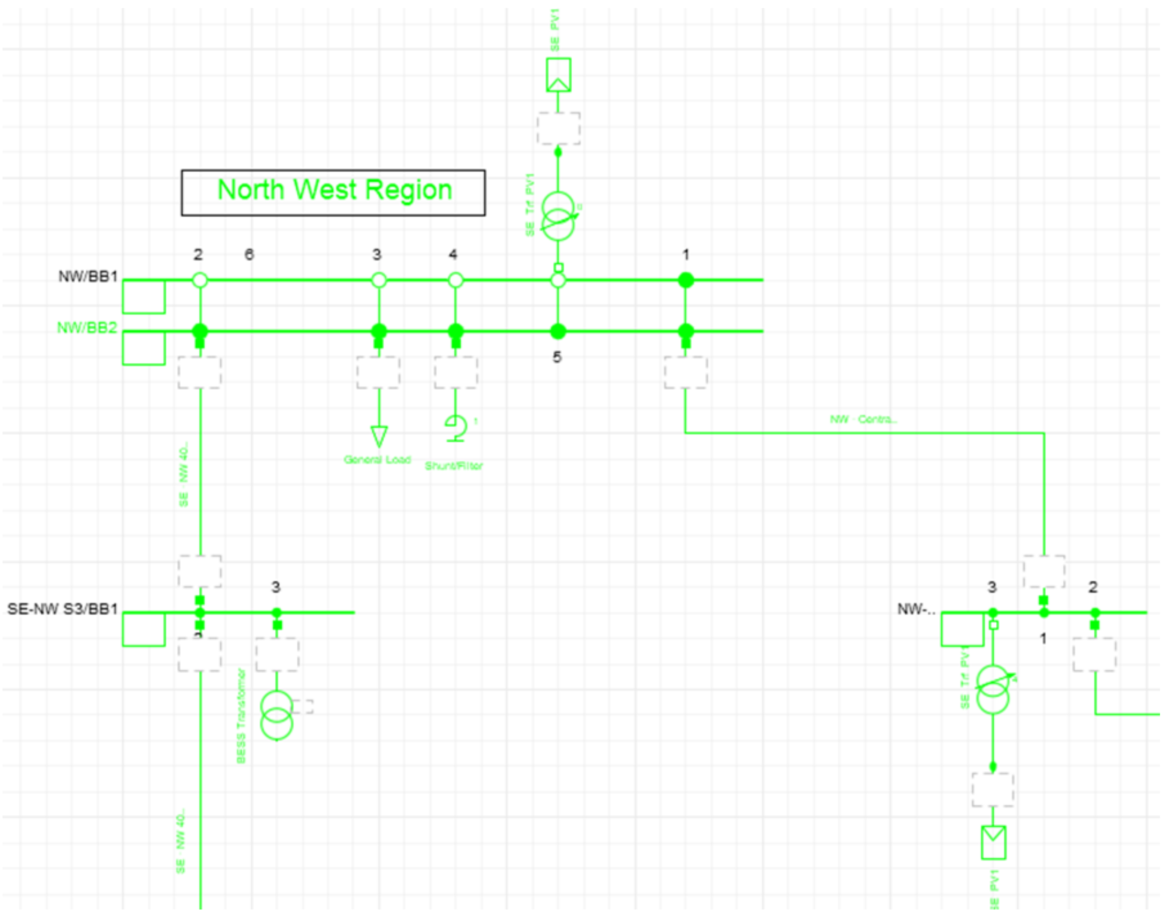

Figure 3.1: The single-line diagram of the base case, North West Region under study

3.3.2 Base Case with BESS implementation

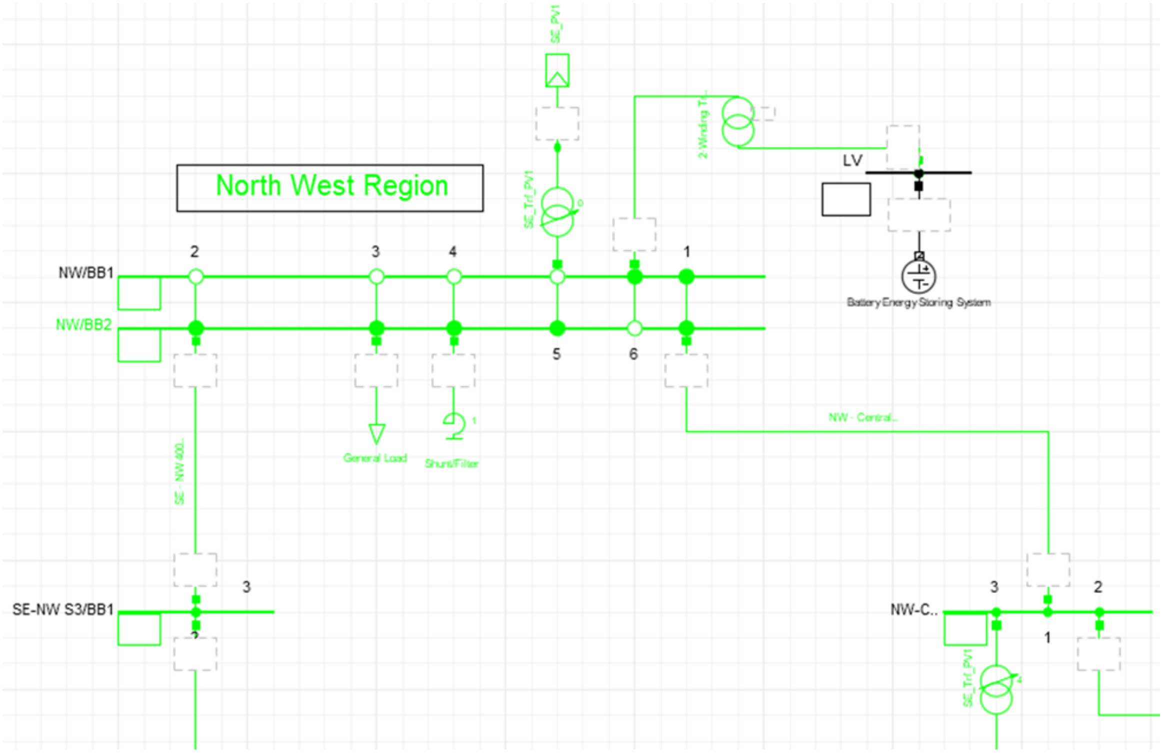

Figure 3.2: Base case with BESS implementation

Location of BESS was chosen to be NW/BB1 in the single line diagram because of the close proximity to PV plants. However the optimal location of positioning the BESS would have to be explored when there is more time as there are various techniques discussed in literature to obtain the optimal location of BESS in the power system. The sizing of BESS was calculated to range from about 30MVA to 100MVA inorder to handle frequency regulation well. The calculation for this is shown in the Appendix A of the report. Parameters for the frequency controller and the PQ controller are shown below.

Parameters	**Value**
Filter time constant (active part) Tr (s)	0.01
Filter time constant (reactive part) Trq (s)	0.1
Proportional gain, Kp (pu)	0.15
Proportional gain, Kq (pu)	1.0
Integration time constant, Tip (s)	0.003
Integration time constant, Tiq (s)	0.002
Minimum discharging current, id_min (pu)	-0.4
Maximum discharging current, id_max (pu)	1.0
Minimum reactive current, iq_min (pu)	-0.1
Maximum reactive current, iq_max (pu)	1.0

Table 3.1: PQ Controller parameters [12]

Parameter	Value
Droop	0.004
Dead band for frequency control (pu)	0.0002

Table 3.2: Frequency controller parameters [12]

3.3.3 PQ Controller Tuning

Figure 2.2 shows a block diagram of the DIgSilent BESS template PV/PQ controller that will be used in this project. Tuning the Kp (Proportional Gain) and Tip (Integrator Time Constant) parameters, key parameters of the proportional-integral (PI) controller within the BESS's PQ controller for active power control is essential for optimal performance.

To tune the PQ Controller, a sensitivity analysis was conducted in DIgSilent PowerFactory. The analysis involved manually adjusting the Kp and Tip parameters while keeping the BESS capacity fixed at 100 MVA, with the goal of identifying values that optimize frequency regulation. This method is similar to that used in [13]. The primary metrics monitored were the frequency nadir and the Rate of Change of Frequency (ROCOF), with a target frequency of at least 49 Hz following a contingency event involving a sudden 50% load increase—representing the project's worst-case scenario. The results showed that a Kp of 0.15 and a Tip of 0.003 yielded the best frequency nadir, reaching 48.71 Hz with a BESS size of 100 MVA.

Figure 3.3 illustrates BESS performance at Kp = 0.15 and Tip = 0.003, where the frequency nadir reaches 48.67 Hz, which is close to the target nadir of 49 Hz after a sudden load increase event.

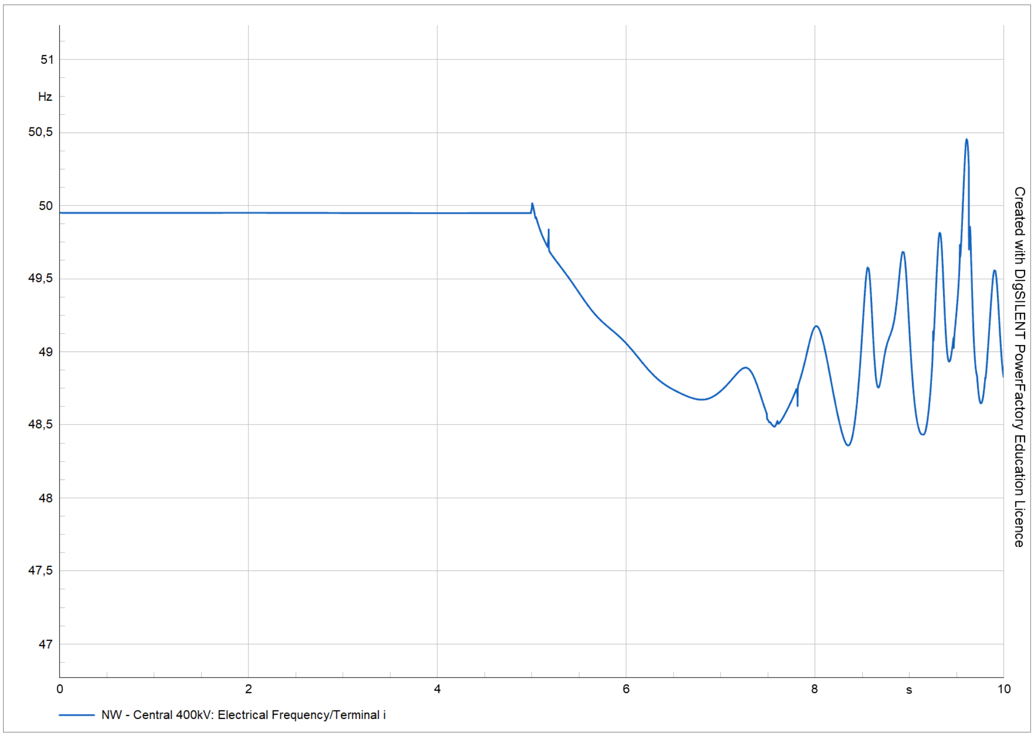

Figure 3.3: Performance of BESS for frequency regulation after tuning

Chapter 4

Results and Discussion

This section presents simulation results for the EMT Analysis, Steady-State Analysis, and Quasi-Dynamic simulations across the cases outlined in the methodology.

4.1 EMT Analysis

The EMT analysis involved simulating a contingency event of a sudden load increase at $t = 5$ seconds to observe its impact on the system's electrical frequency. In these scenarios, PV penetration is held constant. The observed frequency drop, discussed in the following section, results from an imbalance between generation and demand, where demand exceeds generation, causing a decrease in frequency. The EMT simulations were conducted over a 10-second period, and the results are presented below:

4.1.1 Case 1

For this case, we study the effect of a sudden load increase of 10% on the power system frequency stability. This is before BESS has been implemented.

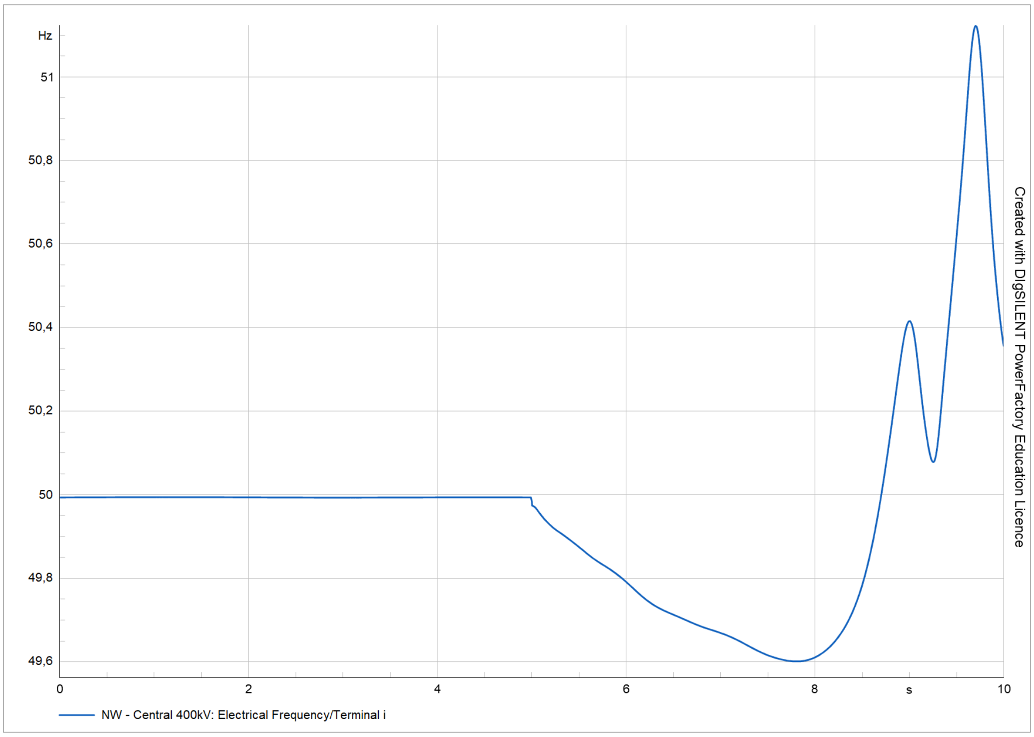

Figure 4.1: Base Case with a sudden load increase of 10%

As shown in the figure above the, the system has a frequency nadir of 49.60Hz. The frequency drop is not too bad because it is only a 10% drop in frequency, hence it is expected. After about t = 6.81 seconds, the system begins to recover but overshoots above the nominal frequency of 50Hz. Oscillations are also observed to be occurring as the system frequency begins to recover.

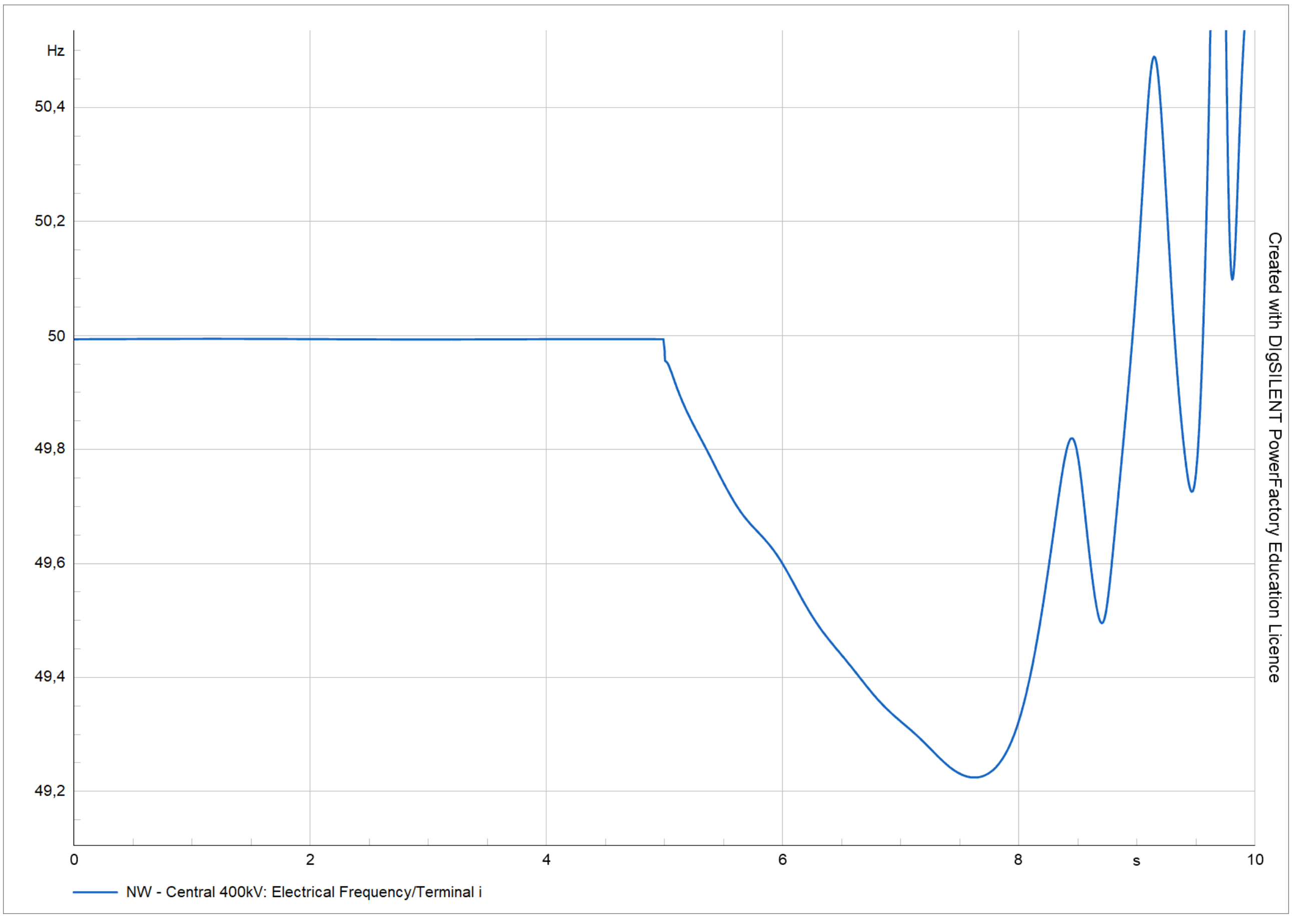

Figure 4.2: Base Case Loading at 20%

The figure above shows the frequency response and at about t = 7.71 seconds, we observe that the system has a frequency nadir of 49.22Hz. After that the system begins to recover but overshoots above the nominal frequency of 50Hz. Oscillations are also observed to be occurring as the system frequency begins to recover.

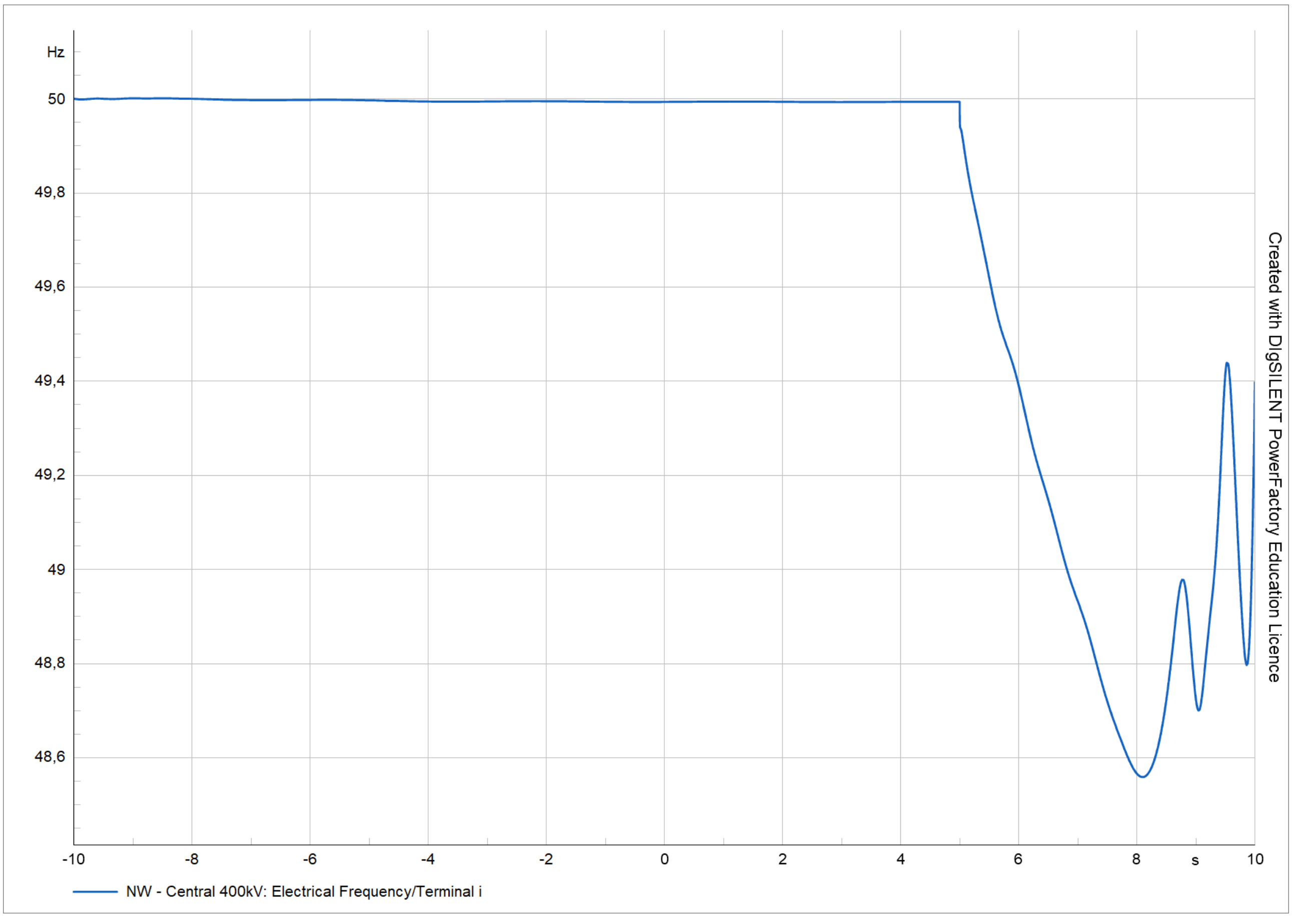

Figure 4.3: Base Case with a sudden load increase of 30%

As shown in the figure above the, the system has a frequency nadir of 48.56Hz at about 8.2 seconds. The system frequency begins to recover but then at a slower rate compared to the previous scenarios. Oscillations are still observed in this section too.

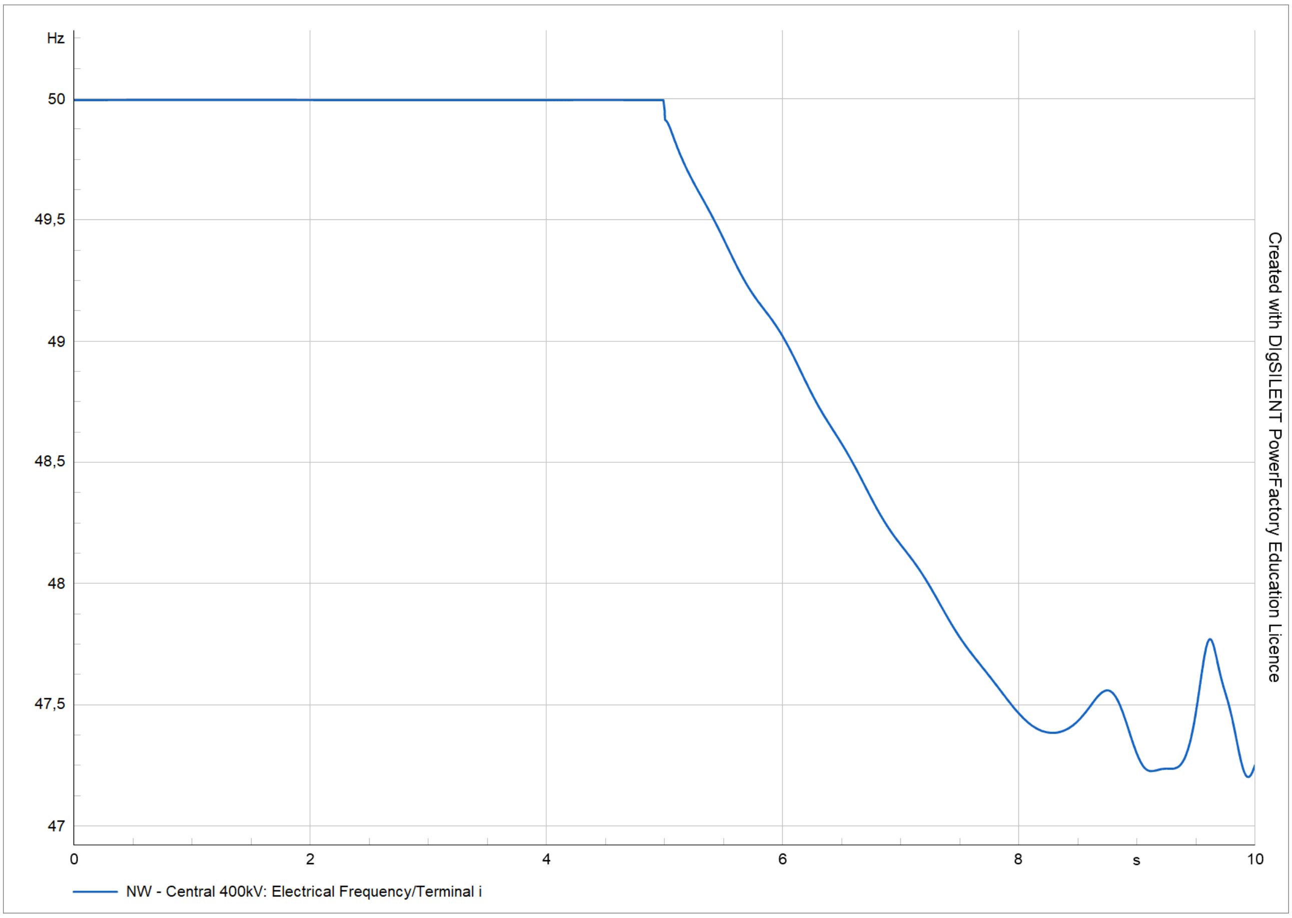

Figure 4.4: Base Case with a sudden load increase of 50%

As shown in the figure above, the system has a frequency nadir of 47.38Hz. This scenario has the slowest rate of recovery after the event of a sudden load increase. The oscillations after the frequency nadir as the system frequency begins to recover are the least compared to the other scenarios.

A key takeaway from the variation of the sudden load increase contingency is that, the higher the magnitude of the load increase, the deeper the frequency fall will be.

4.1.2 Case 2

For this section we implement BESS inorder to try improve the frequency nadir whilst also observing the ROCOF(Rate of Change of Frequency) which are some of the key indicators for frequency stability analysis. The process done for the previous case is repeated and test out using different scenarios of load increase in order to compare if there is an improvement in terms of the parameters we are monitoring of frequency nadir and the ROCOF.

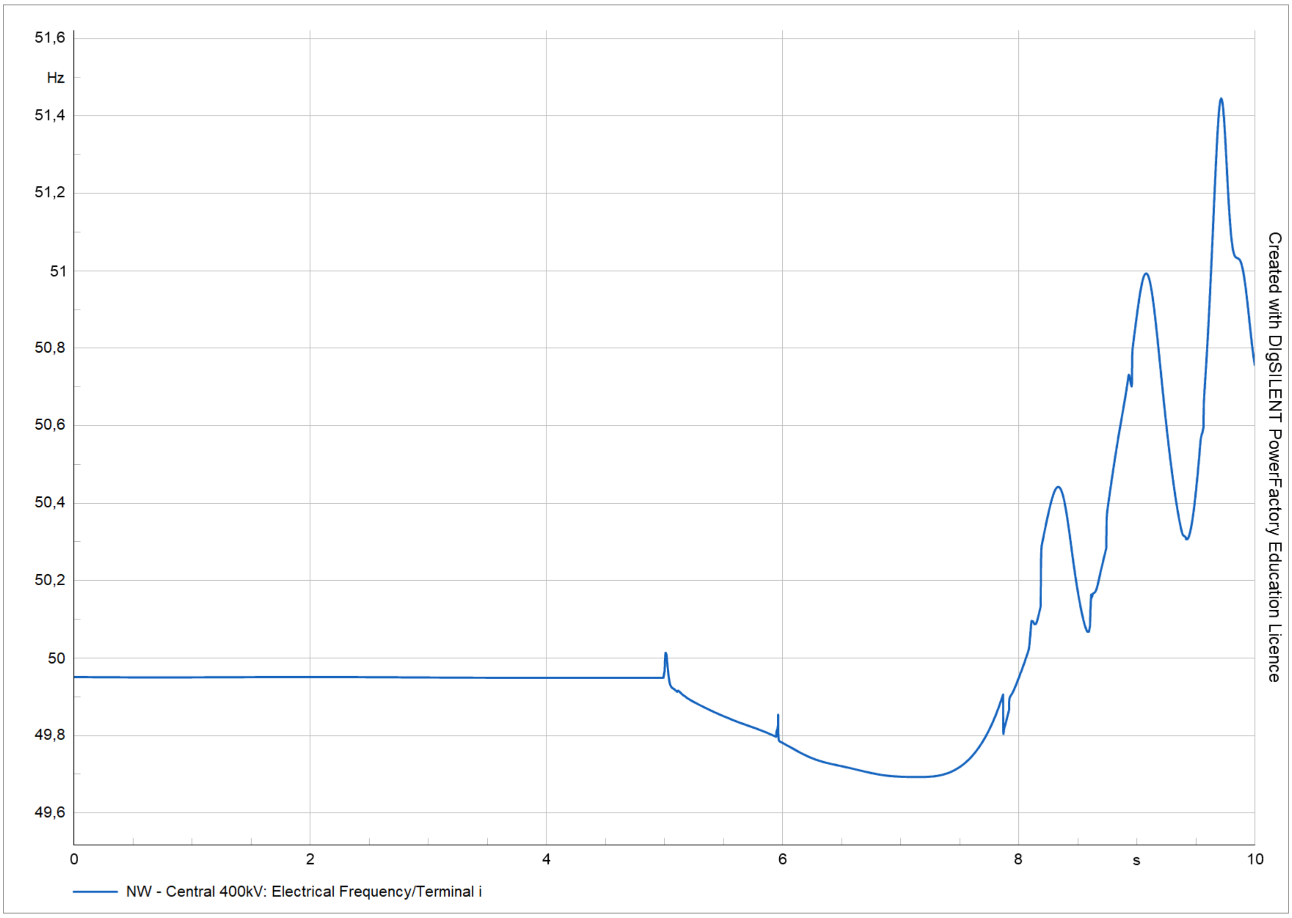

Figure 4.5: Base Case with BESS integration and load increase of 10%

As shown in the figure 4.5 above the, the system has a frequency nadir of 49.69Hz at about 7.2seconds. The frequency begins to recover after this however it overshoots. The overshooting could be corrected by trying to retune the BESS PV/PQ controller, particularly the Kp and Tip parameters. This is an improvement in frequency response when compared to case A, in fig 4.1 as seen by the improved ROCOF and frequency nadir.

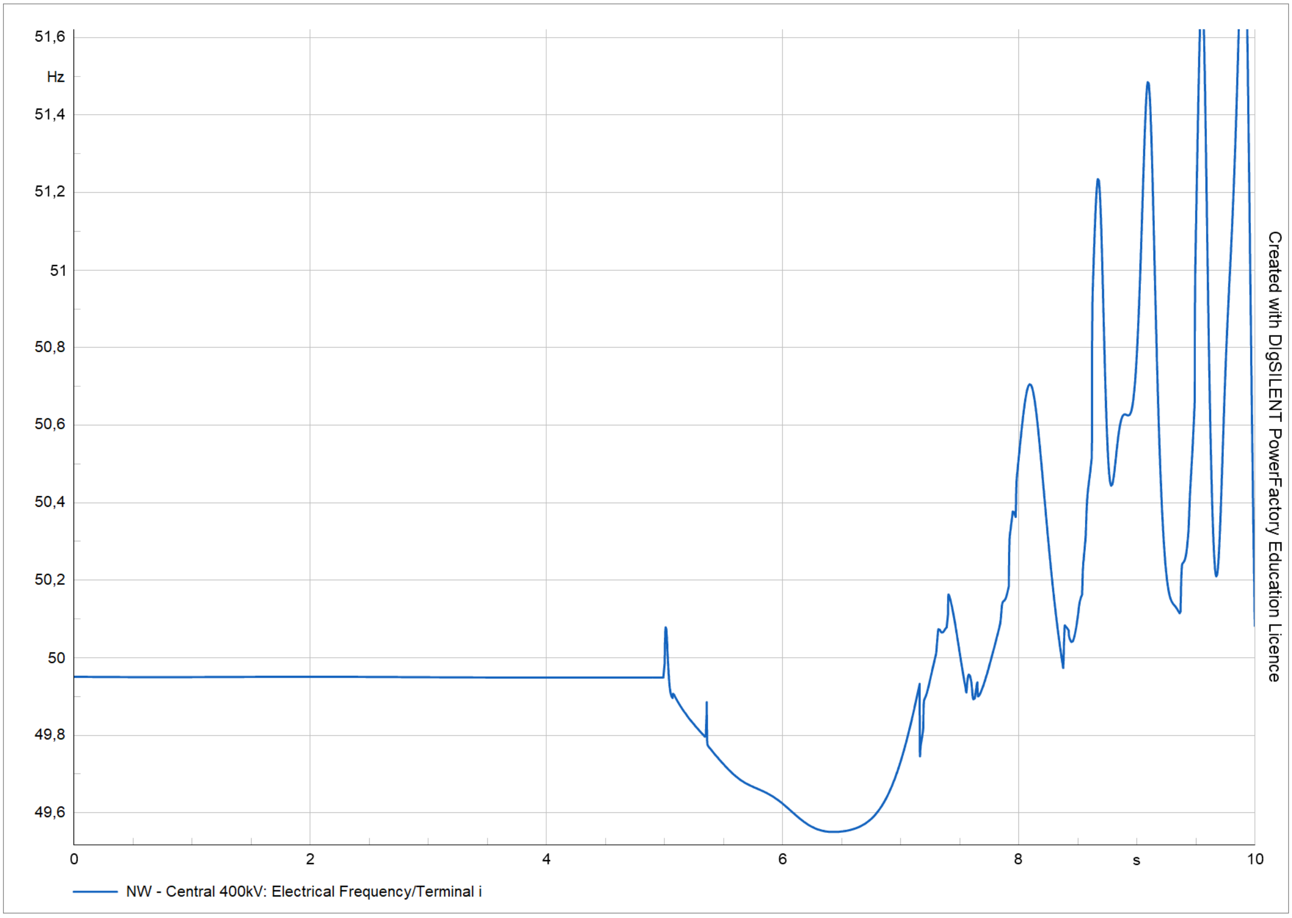

Figure 4.6: Base case with BESS integration, subjected to a sudden load increase of 20%

After the sudden load increase at 5 seconds, there is an imbalance of generated power and demand hence the result is shown. As shown in the figure 4.6 above, the system has a frequency nadir of 49.55Hz at about time t = 6.3 seconds. Oscillations and overshooting are also observed to be there as the system begins to recover. The results obtained show that there is a slight improvement in frequency response as seen by the improved ROCOF and frequency nadir.

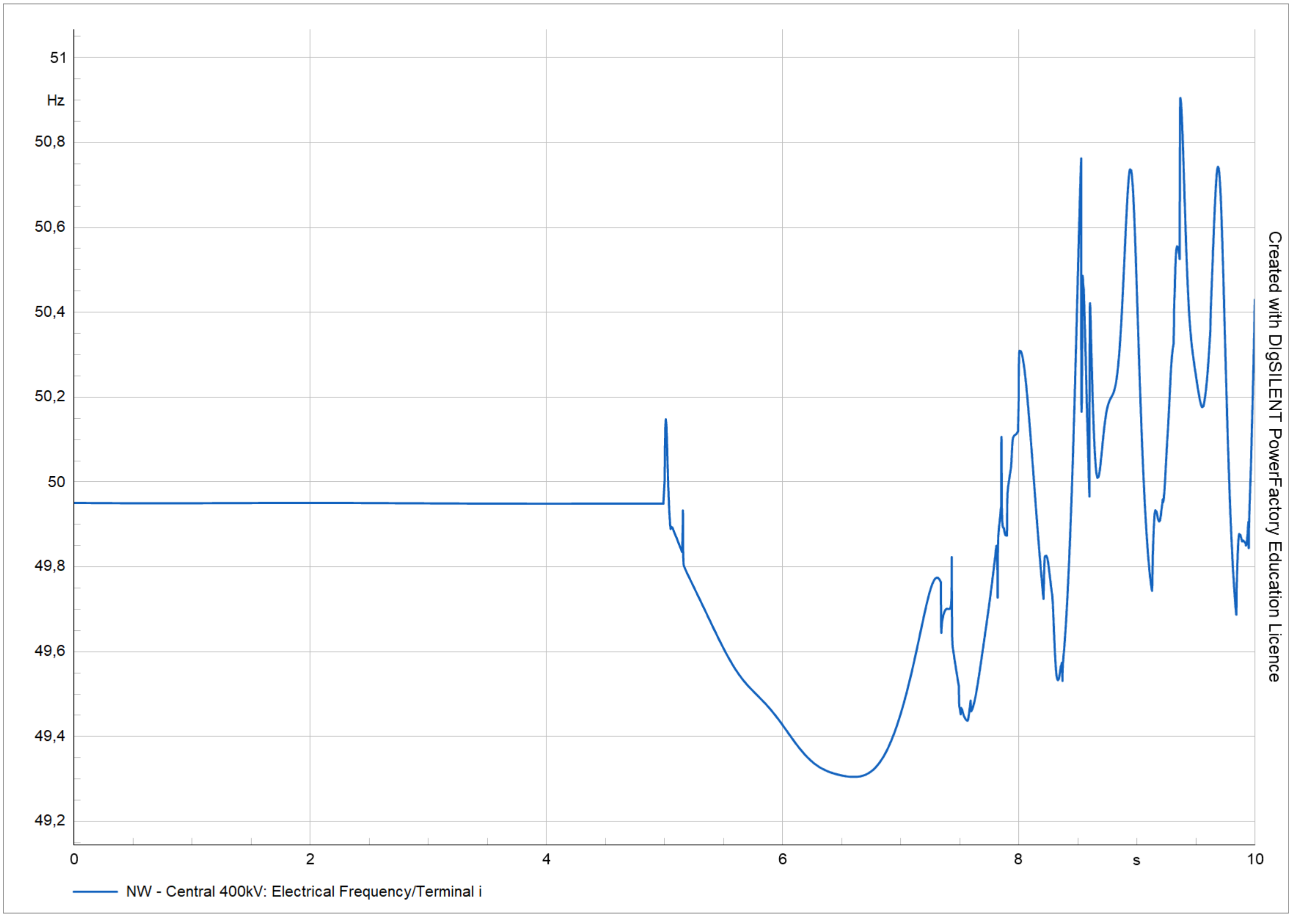

Figure 4.7: Base case with BESS integration, subjected to a sudden load increase of 30%

As shown in the figure 4.7above the, the system has a frequency nadir of 49.31Hz at time t = 6.41 seconds. Which is also an improvement in frequency response when compared to 4.3. Oscillations are more pronounced in this scenario.

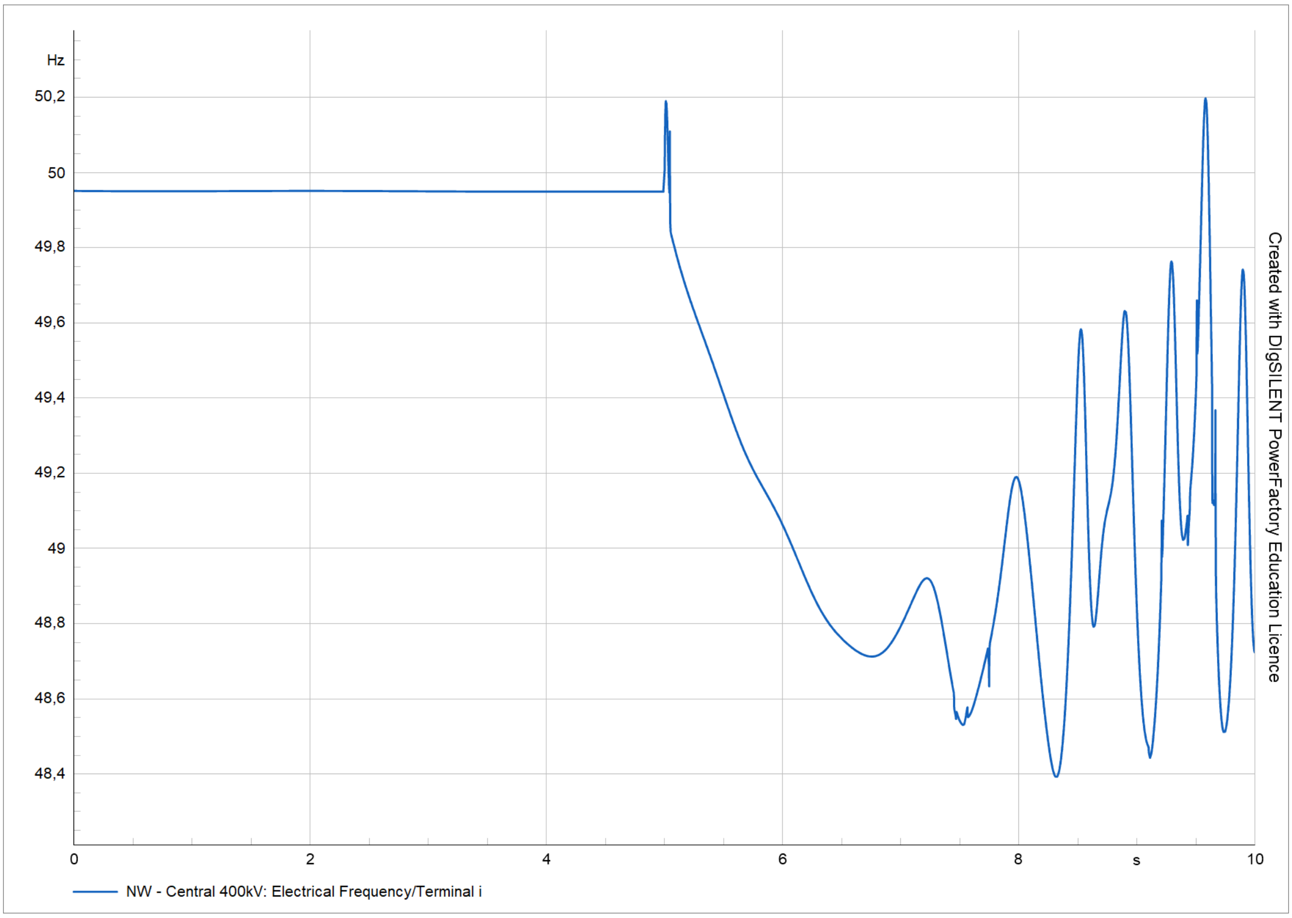

Figure 4.8: Base case with BESS integration, subjected to a sudden load increase of 50%

The frequency nadir for this figure 4.8 is 48.71Hz at time t = 6.46seconds, which is an improvement in frequency response after BESS has been implemented.

The table 4.1 shows a summary of the results obtained for Case 1 and Case 2

Load Increase (%)	Frequency Nadir when no BESS (Hz)	Frequency Nadir when BESS implemented (Hz)
10	49.6	49.69
20	49.22	49.55
30	48.56	49.31
50	47.38	48.71

Table 4.1: Frequency Nadir with and without BESS at different load increases

4.1.3 Case 3

For this section,I present results of how BESS size affects the frequency resposnse.

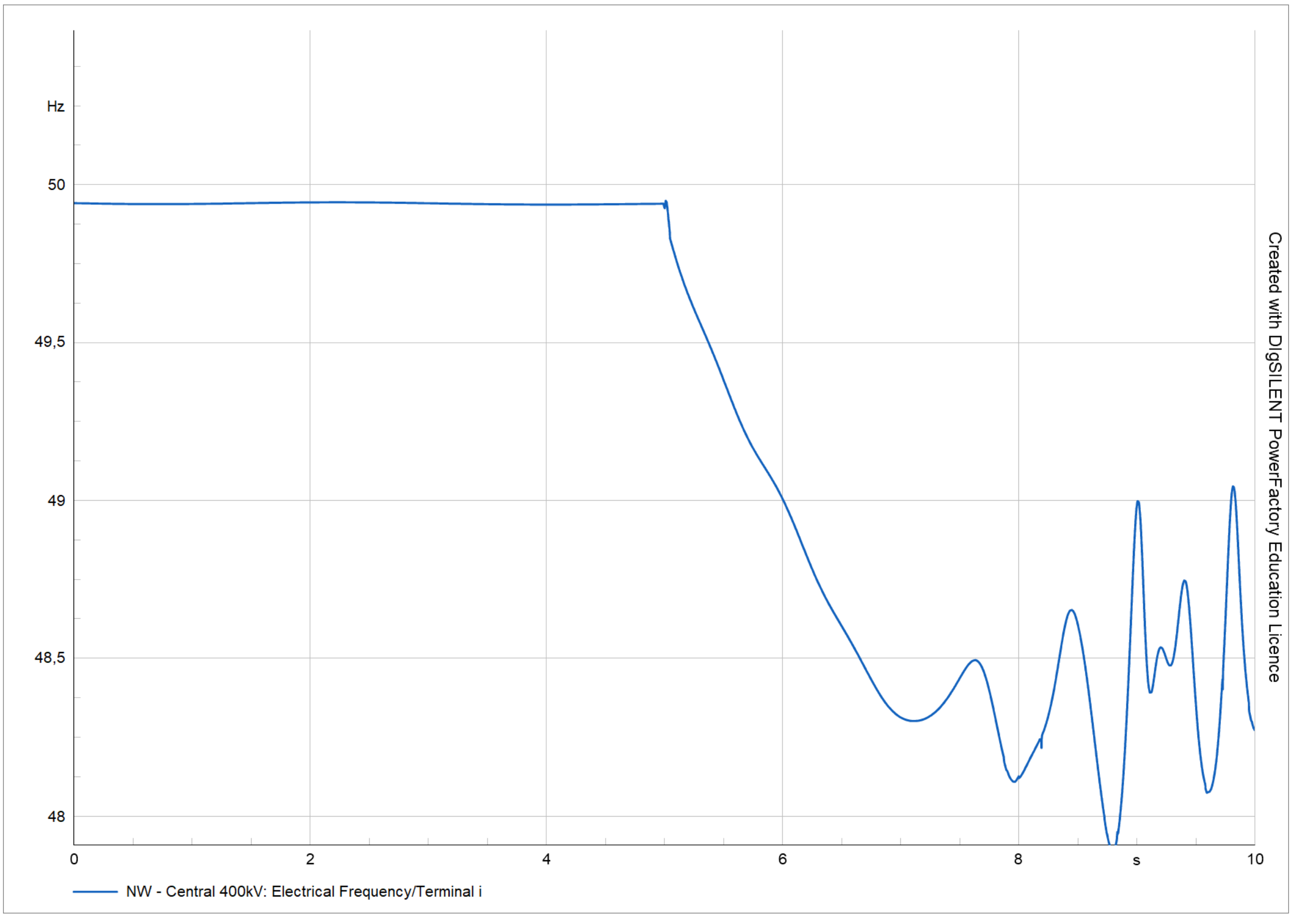

Figure 4.9: Base case with BESS size of 30MVA

The figure 4.9 shows an improvement in the system's response, as there is no overshooting during the recovery from the contingency event. The Frequency nadir is at 48.30 Hz at time t = 7.09 seconds.

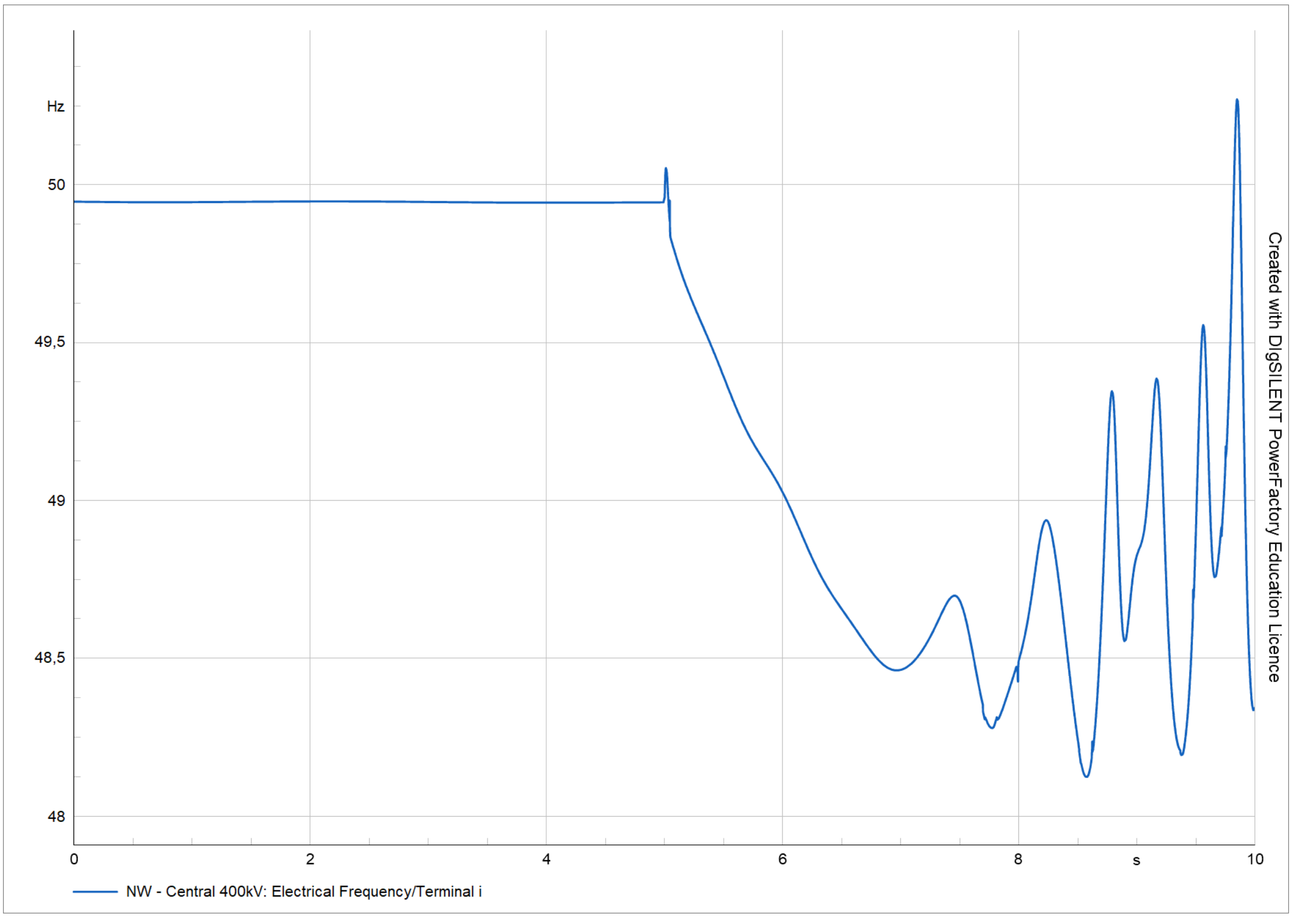

Figure 4.10: Base Case with BESS size of 60MVA

Oscillations start to appear a bit more as in the figure 4.10. Frequency nadir was observed to be 48.46Hz at time t = 7.03 seconds

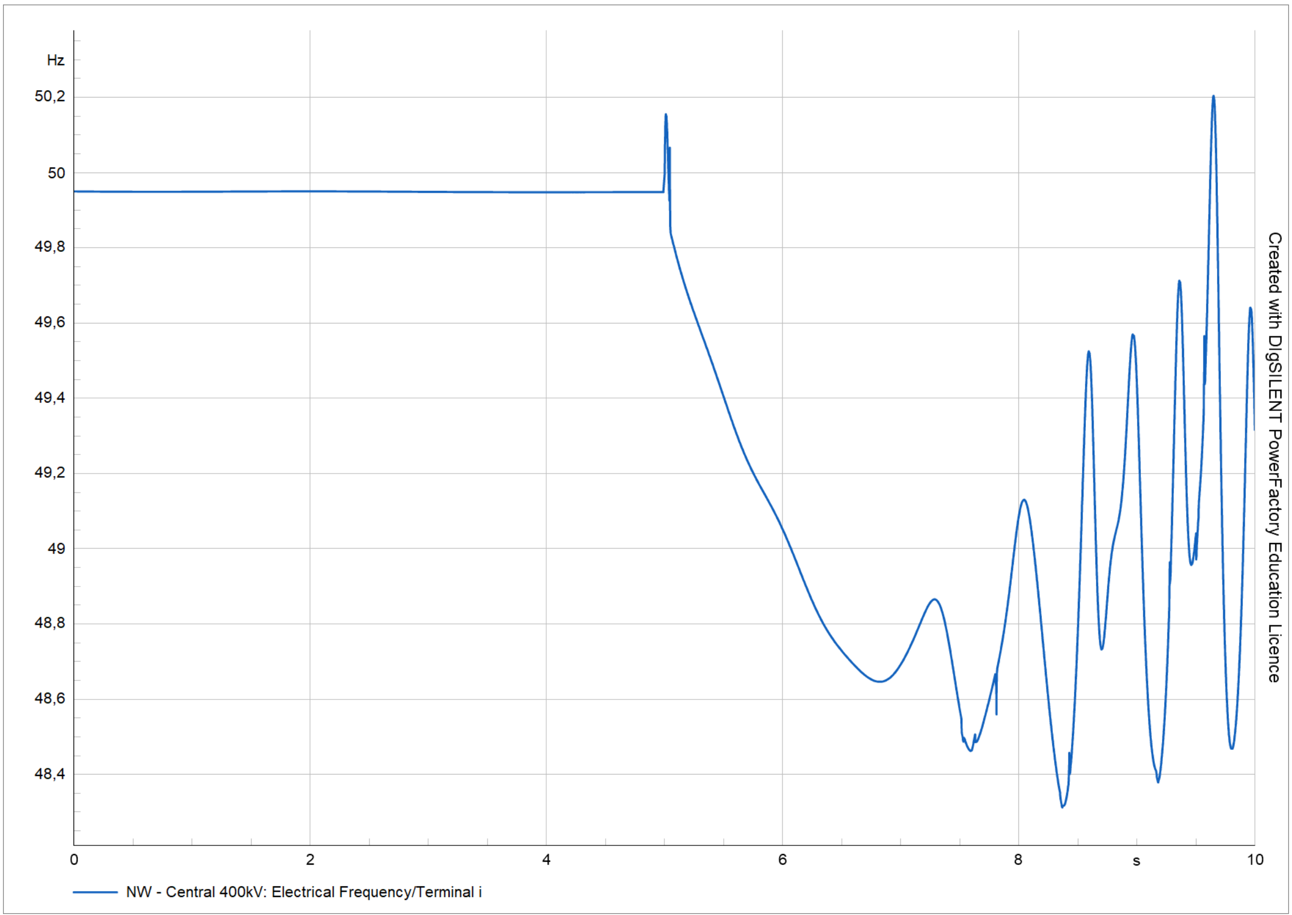

Figure 4.11: Base case with BESS size 90MVA

Summary of results for this section is shown below:

BESS Size (MVA)	Frequency Nadir (Hz)
30	48.3
60	48.47
90	48.65
100	48.71

Table 4.2: BESS Size and Corresponding Frequency Nadir

From the results obtained in the Case 3 of the EMT simulation we observed that the best performance for frequency support was obtained at a high BESS capacity of 100MVA. This result also agrees with what was observed in literature by [12]. However there were greater oscillations being observed as the BESS capacity was being increased. This could be attributed to the tuning of BESS PV/PQ Controller parameters, Kp and Tip as mentioned in [12], which could be improved by using an optimization approach such as that done in [13].

The image shown below shows the active power that is injected by BESS after a sudden load increase occurs.

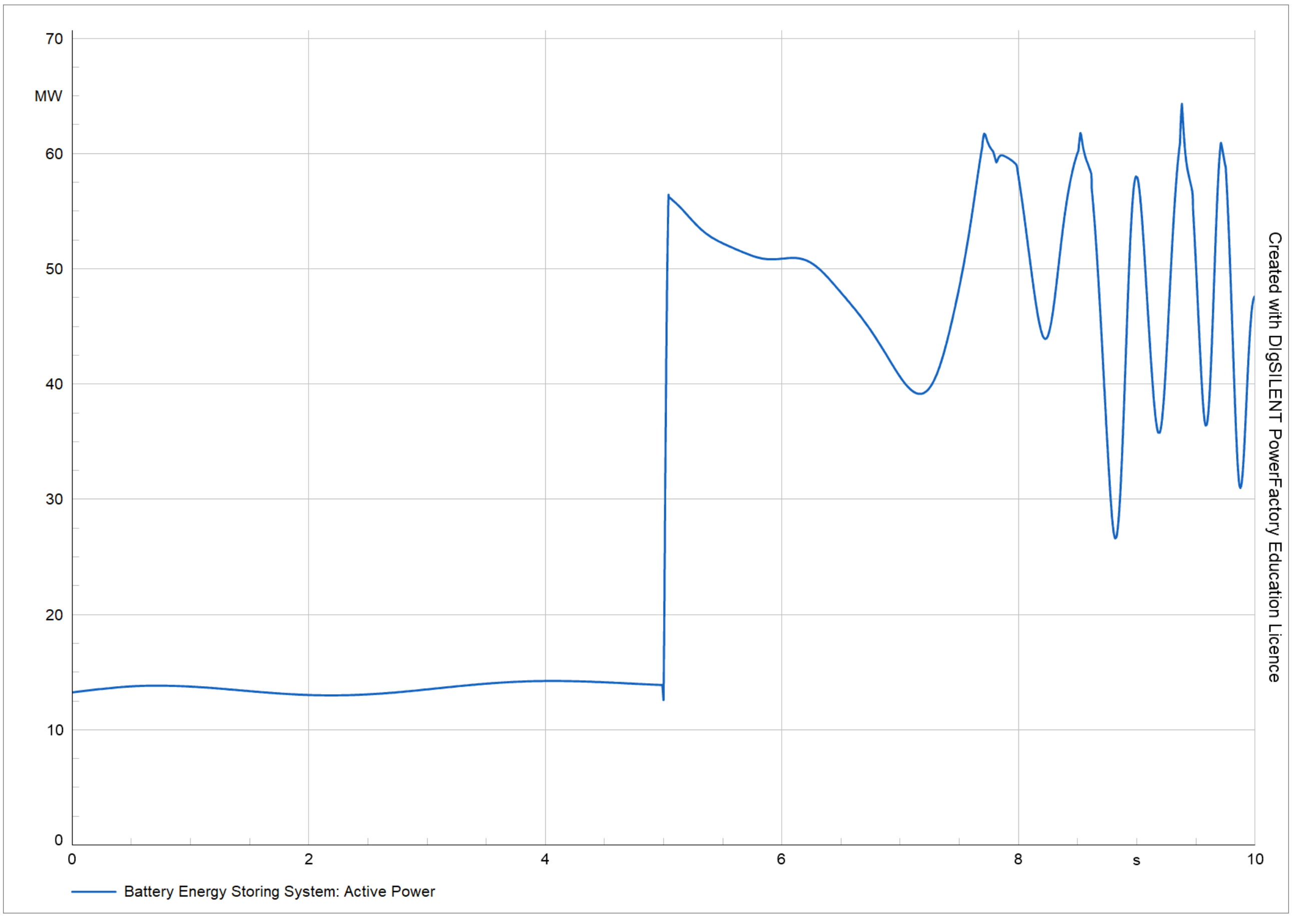

Figure 4.12: Active power injection by BESS after sudden load increase

About 57 MW of active power is injected by 100MVA BESS after a sudden 50% increase in load demand. BESS was observed to be providing synthentic inertia through ccontrolled discharge of energy. In this part of the simulations, we observed how BESS can help to rapidly inject active power into the grid during an under frequency event, in order to counteract the frequency drop and this supports what was claimed in [12]. The frequency controller ensures the energy is discharged in a controlled manner to support grid and severe frequency deviations. In this section we also observed how increasing the size of BESS can help to keep the frequency drop within acceptable limits which also supports the observation done in [12].

4.2 Steady State Analysis

In this section, the approach used for voltage stability analysis is the one outlined in the methodology for calculating the voltage stability index.

4.2.1 Case 1

The figure 4.13 shows a figure of part of the single line diagram representing the transmission line under analysis.

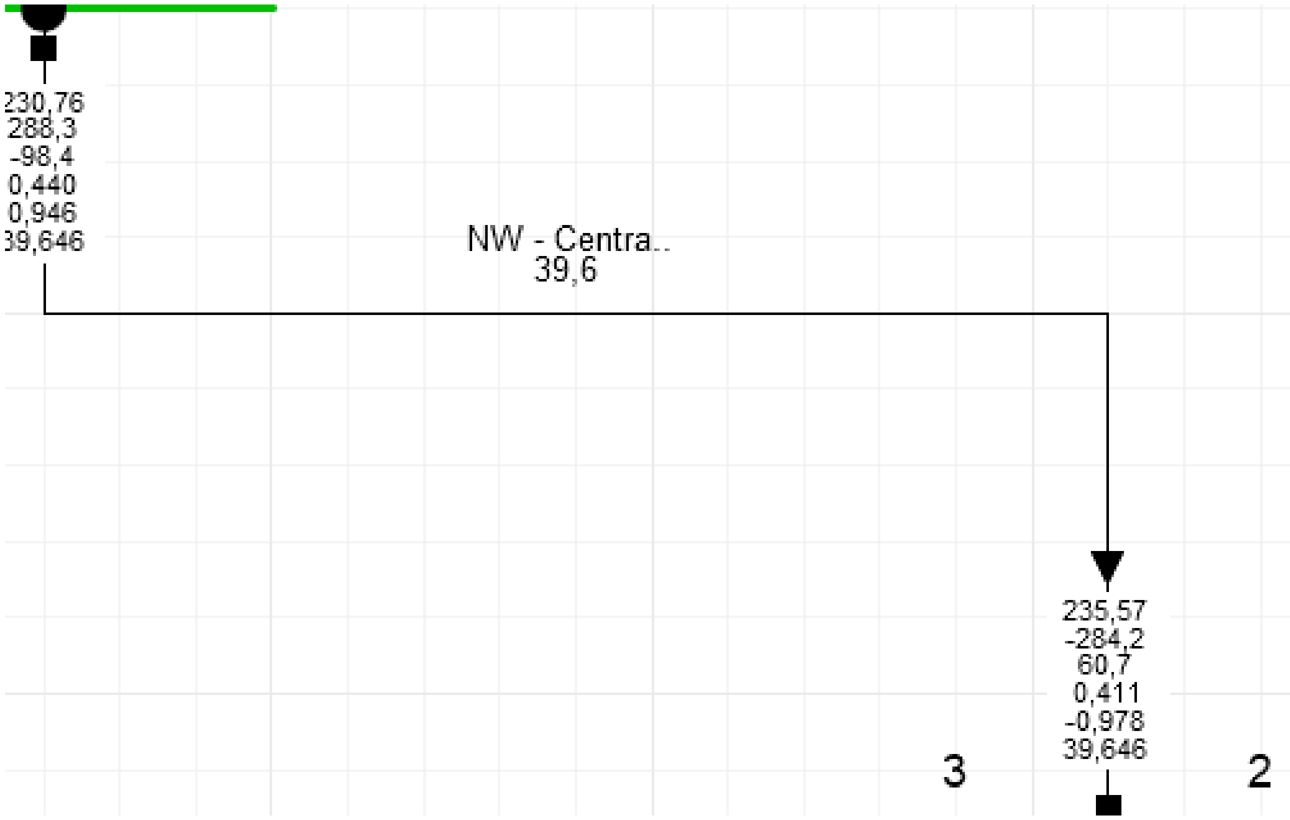

Figure 4.13: Transmission Line NW-Central 400kv under analysis

Parameter	Value
Line Impedance (Z)	69.90716 Ω
Reactive Power (Q_r)	60.7 Mvar
Sending Bus Voltage (V_s)	230.76 kV
Line Reactance (X)	69.48023 Ω

Table 4.3: Parameters and their values for the FVSI calculation

The parameters that are being monitored and the values are shown in the table 4.3 above: Using equation 3.1 and substituting the values of the parameters in table 4.3, the FVSI for transmission line NW-Central 400kV can be calculated to be 0.32 which shows that it is relatively stable since it is not close to 1.

4.2.2 Case 2

Parameter	Value
Line Impedance (Z)	69.90716 Ω
Reactive Power (Q_r)	57.9 Mvar
Sending Bus Voltage (V_s)	229.75 kV
Line Reactance (X)	69.48023 Ω

Table 4.4: Updated parameters and their values for the FVSI calculation

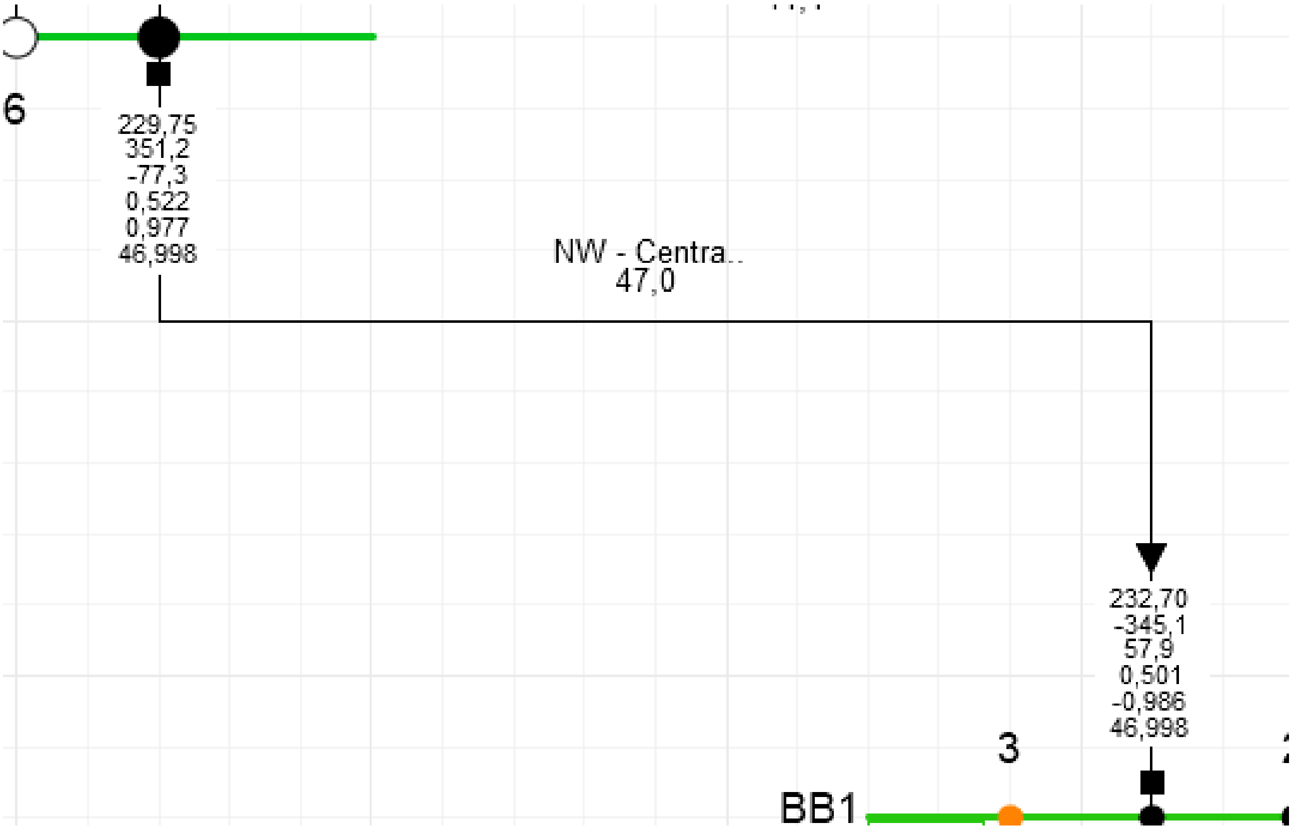

Figure 4.14: Transmission Line NW-Central 400Kv under analysis for Case 2

Using equation 3.1, the FVSI for transmission line NW-Central 400kV can be calculated to be 0.308 after the BESS has been introduced. 0.308 is closer to 0, meaning according to [8] BESS integration has enhanced the voltage stability of the power system.

4.2.3 Case 3

In this section, a study on the impact of varying the size of BESS on the value of the voltage stability index(FVSI) is presented.

Table 4.5: BESS Size and FVSI

BESS Size (MVA)	FVSI
30	0.308
60	0.308
90	0.308
100	0.308

The results obtained showed that changing the BESS size from 30MVA to 100 MVA does not change the voltage stability index as shown in table 4.5. This could be because we are already analyzing a highly stable transmission line since the correct procedure for choosing the transmission line for analysis was not done correctly. The first step in using the FVSI is to identify lines that are heavily loaded or have the potential to become heavily loaded. This was not done, however, I identified that the line NW-Central 400kv connects critical buses hence the decision to analyze this line.

4.3 Quasi-Dynamic Simulation

In this section he simulation aims to capture the behavior of the power system under varying time-of-day conditions.

The active power in the transmission line was observed to remain the same for each variation of penetration

4.3.1 Case 1

For the base case, the effects of varying the PV penetration levels on the active power in (10%, 20% and 30%) are demonstrated below.

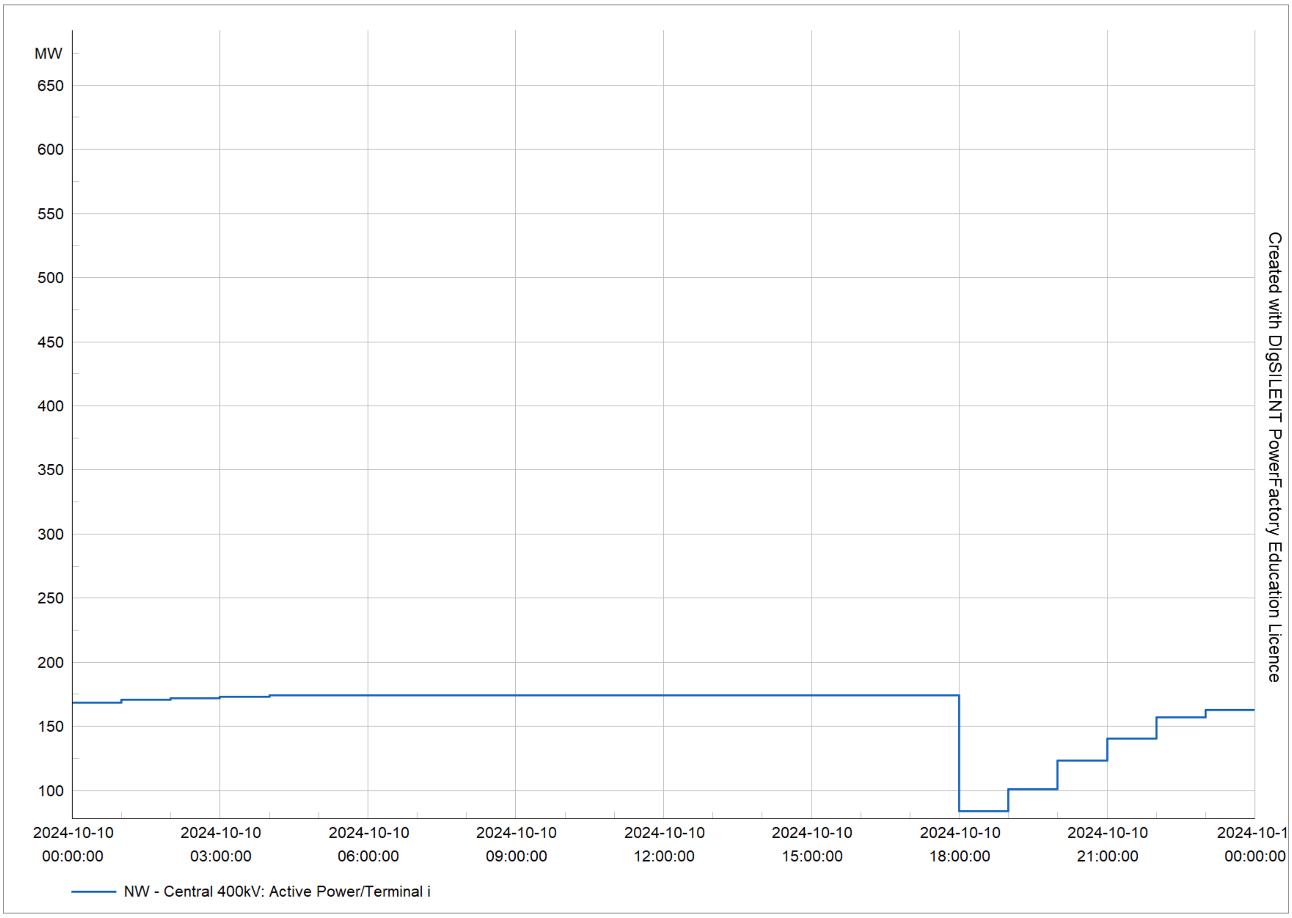

Figure 4.15: Base Case with 10% PV penetration

The results for other penetration levels, 20% and 30% was observed to be remaining the same after changing it hence for PV penetration levels 20% and 30% the plots look exactly the same as the one shown in figure 4.15.

4.3.2 Case 2

Results for the case where BESS has been integrated and has the same capacity of 60MVA whilst varying the PV penetration levels are shown below:

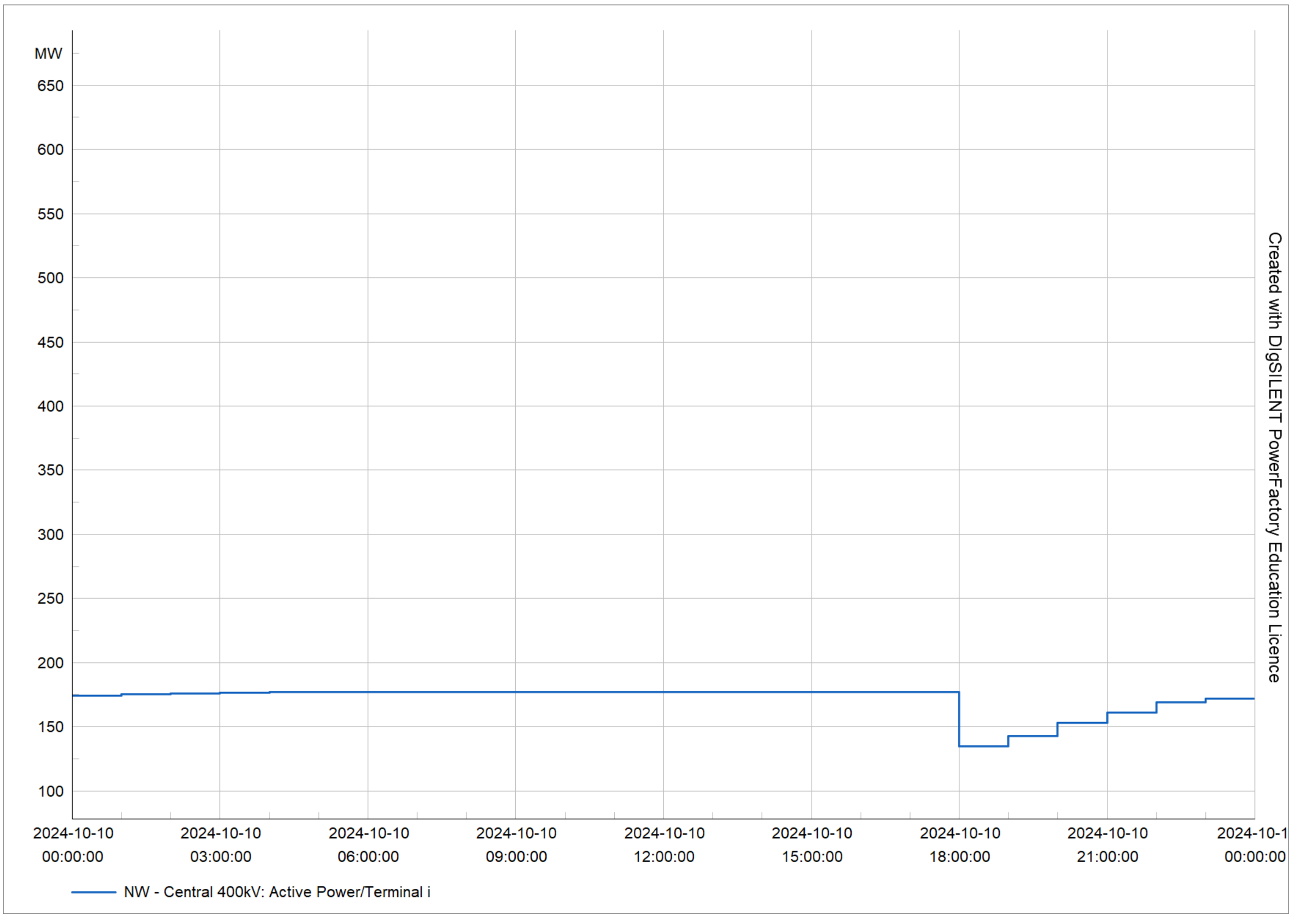

Figure 4.16: Base Case with BESS integration at 10% PV penetration.

The result shown above was the same for the other PV pentration levels 20%, and 30%. Compared to Case 1, we observe that the active power in the NW-Central 400kV line was smoother in Cae 2 than in Case 1. This is because BESS was charging during periods of low demand(06:00 to around 18:00) and discharging active power during peak demands (morning and evening) hence resulting in smoother plots of active power.

4.3.3 Case 3

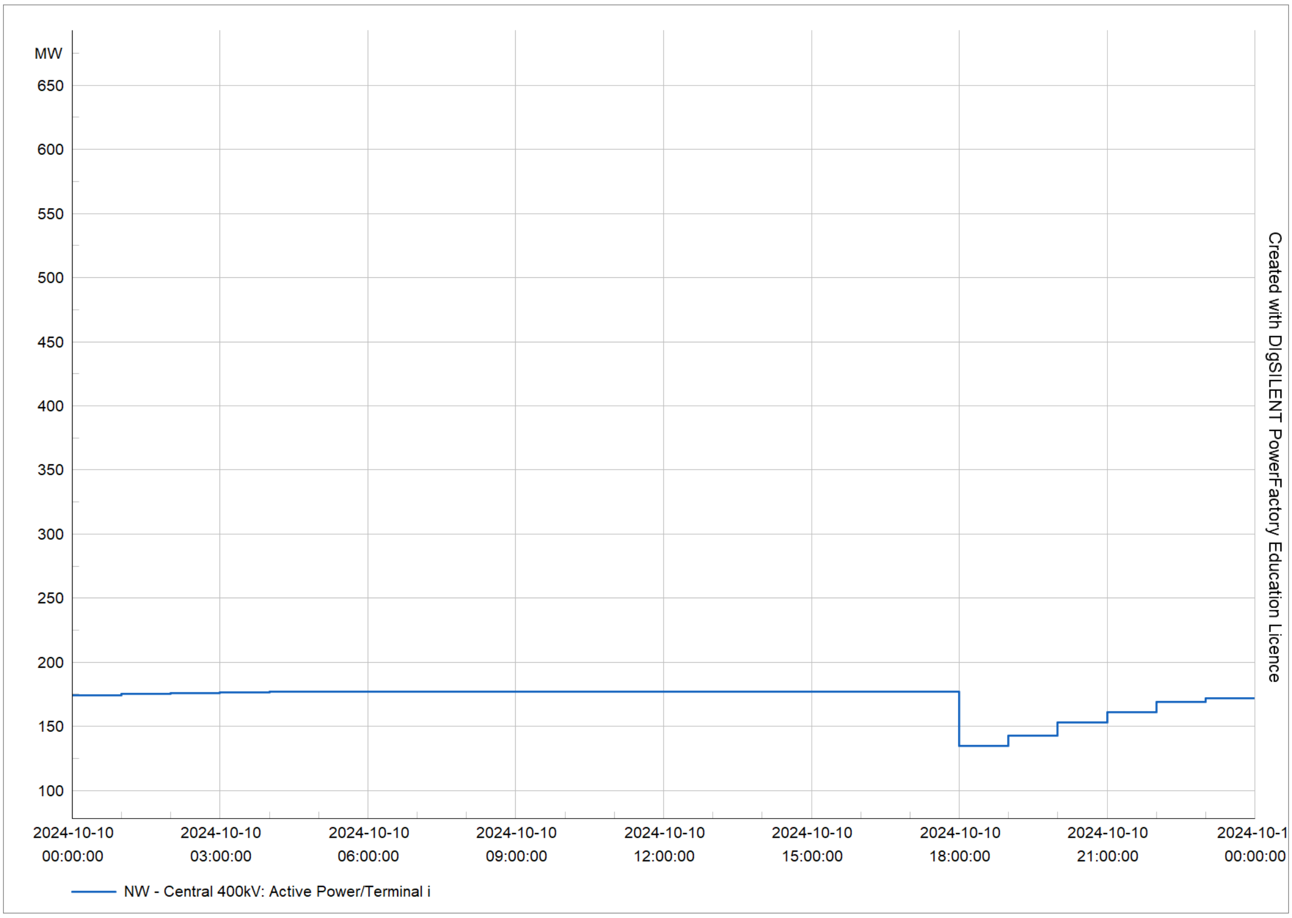

Figure 4.17: Base Case with BESS integration at 30% PV penetration and BESS capacity 60MVA.

From the results obtained in the Quasi-Dynamic simulations, cases 1 to 3, we observed that in Case 1 before BESS was introduced, there were more extreme peaks and troughs in the active power plot of the transmission line compared to Case 2 after BESS was introduced to the grid. The active power plot shown seems to be smoother in Case 2 when compared to Case 1 when there was no BESS. This can be attributed to how BESS stores excess power during low demand and discharges it during peak demand period. This observation also validate the findings in literature mentioned by [18, 19]. From the results of Case 1 to 3 we can conclude that connecting BESS to the grid enhances the power transfer in transmission lines by making the active power flow to be more balanced and stable over the 24hour period.

From the experiments conducted we observed that as the time of day varies, the solar irradinace will vary based on what time of day it is. In the morning between the hours of 00:00 to 06:00, the least amount of solar irradiance is observed. Between 06:00 and 18:00, solar irradiance gradually increases and peaks at midday before gradually starting to decrease until 18:00. Between 18:00 and 00:00, the least amount of solar irradiance is observed too. Other factors such as cloud cover affect the solar irradiance. As solar irradiance varies, the PV penetration varies throughout the day thereby varying the amount of power being generated by PV thrghout the day leading to intermittency. We observed in the EMT Analysis that increasing the size of BESS can help with frequency support. A bigger BESS size, helps the frequency respond quicker after an under frequency event because more active power can be injected by a bigger BESS. This can also lead to better enhancement of transfer capacity in transmission lines.

Chapter 5

Conclusions

The purpose of this project was to study the impact of battery energy storage systems in improving grid stability and to study how battery battery energy storage systems improve the power transfer capacity of tranmsission lines for a time based operation. The report begins with a background to the study and an overview of what motivated the study. A comprehensive literature review that focuses on energy storage systems and grid stability helped shed light to how BESS can help mitigate issues of intermitency caused by renewables such as wind and solar.

The majority of the work for the project followed in formulating a methodology in order to find a way of coming up with a relationship between Solar irradiation, power transfer capacity, time of day, size of BESS and PV penetration. In this methodology, 3 approaches were outlined to tackle this problem formulation. In chapter 3, the design of the power system under study was outlined.

In chapter 4, results and discussions were presented in-order to analyse and use them to create a theoratical formulation of a relationship between solar irradiation, power transfer capacity, time of day, size of BESS and PV penetration. In this section we concluded that solar irradiance varies according to the time of day it is. Size of BESS and PV penetration affect the amount of active power being injected into the power system.

In summary, the project successfully achieved its goals by modeling and presenting results that validate the initial hypothesis.

Chapter 6

Recommendations

Exploring better ways of optimizing and tuning the BESS PV/PQ controllers would be beneficial in order to improve the performance of BESS in grid stability and transfer capacity optimization. Better tuning of Tip and Kp parameters, will result in better power quality. Improper tuning could lead to oscillations in the system as observed earlier when BESS PV/PQ controller tuning was being done. Another recommendation would be to try to have the latest results for solar irradiance being easy to find and access. The results of solar irradiance for the Northern Cape were not too easy to find and were not the latest results. More recent results can provide a better understanding of what the

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Appendix A

GA Requirements

GA	Requirement	Justification and section in the report
1	Problem-solving	In Chapter 3 and 4, I formulated a method to solve the relationship between solar irradiation, power transfer capacity, time of day size of BESS and PV penetration. The analysis made from those section and using literature studied helped to formulate a relationship
4	Investigations, experiments and data analysis	In chapter 4 of the report, several experiments were done that were structured as Cases 1 to 3. The results obtained from DIgSilent powerfactory were presented in chapter 4 and were then analyzed.
5	Use of engineering tools	DIgSilent Powerfactory software was used to simulate power system models
6	Professional and technical communication (Long report)	Findings of this study were presented in a report and sources were cited using IEEE referencing style
8	Individual work	I conducted investigation individually under the supervision of Dr David Oyedokun.
9	Independent learning ability	I conducted research on the topic independently found in the Literature review section of my report

Appendix B

Use of AI

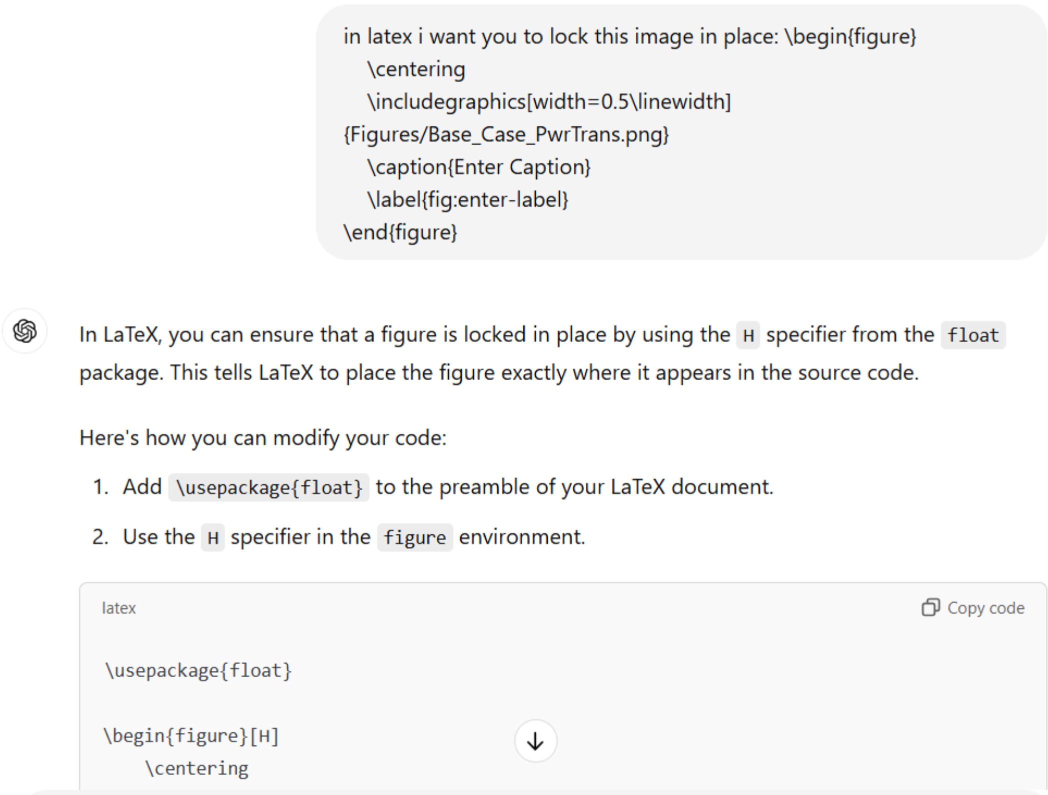

Figure B.1: Using ChatGPT how to format stuff in latex

In figure B.1 I used chatgpt to find help on how to lock my images onto the same page when more content is being added to it.

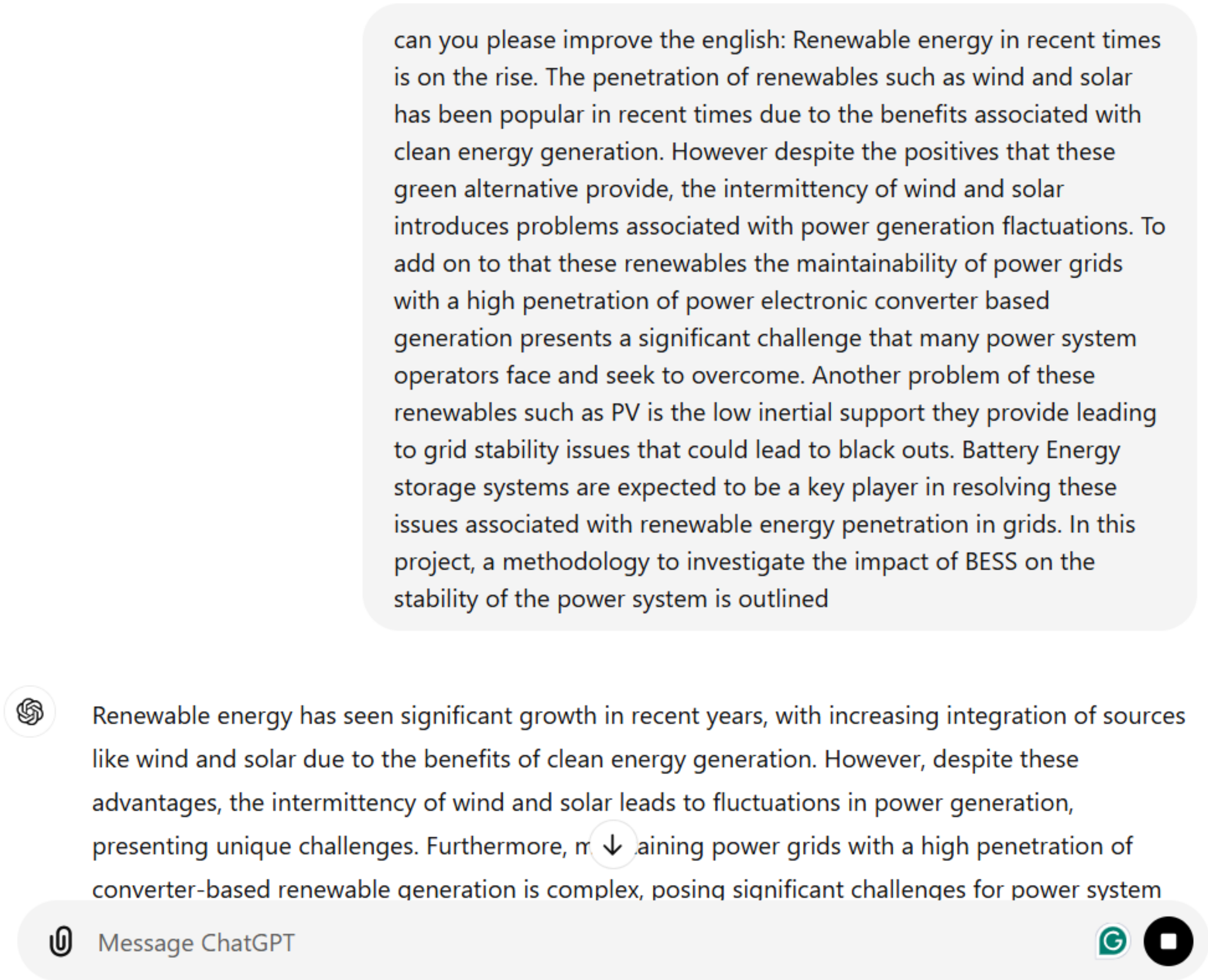

Figure B.2: Using ChatGPT to correct my grammar

In the figure B.2 I used chatgpt to help correct my grammar and spelling. The picture shown is an example for when I used it for improving my English when I wrote my Abstract. This was done for other sections of the report as well.

Appendix C

GitHub Link to model file

GitHub Repository

Appendix D

Additional Calculations and Data

D.1 BESS Sizing for PV Plant

1. Recommended BESS Power Capacity

The BESS power capacity can be sized up to 10% of the total PV capacity [20]:

$$\text{BESS Size (MW)} = 360\,\text{MW} \times \left(\frac{10}{100} \text{ to } \frac{30}{100}\right)$$

$$\text{BESS Size (MW)} = 36\,\text{MW to } 108\,\text{MW}$$

Based on the above calculation, a BESS sized between 36 MW and 108 MW.

D.2 Solar irradiance Data from PVGIS database [21]

Time (UTC+2)	G(n)	Gb(n)	Gd(n)
00:00	0.00	0.00	0.00
01:00	0.00	0.00	0.00
02:00	0.00	0.00	0.00
03:00	0.00	0.00	0.00
04:00	0.00	0.00	0.00
05:00	0.00	0.00	0.00
06:00	9.97	7.62	2.09
07:00	549.18	409.12	127.42
08:00	802.45	606.47	174.46
09:00	925.96	713.52	190.42
10:00	998.04	793.92	187.20
11:00	1030.19	837.26	182.54
12:00	1030.03	837.16	186.39
13:00	1036.60	837.55	191.49
14:00	1015.98	821.45	181.67
15:00	975.35	764.72	191.15
16:00	899.38	688.99	187.36
17:00	767.15	573.75	173.39
18:00	482.15	356.31	117.29
19:00	0.00	0.00	0.00
20:00	0.00	0.00	0.00
21:00	0.00	0.00	0.00
22:00	0.00	0.00	0.00
23:00	0.00	0.00	0.00

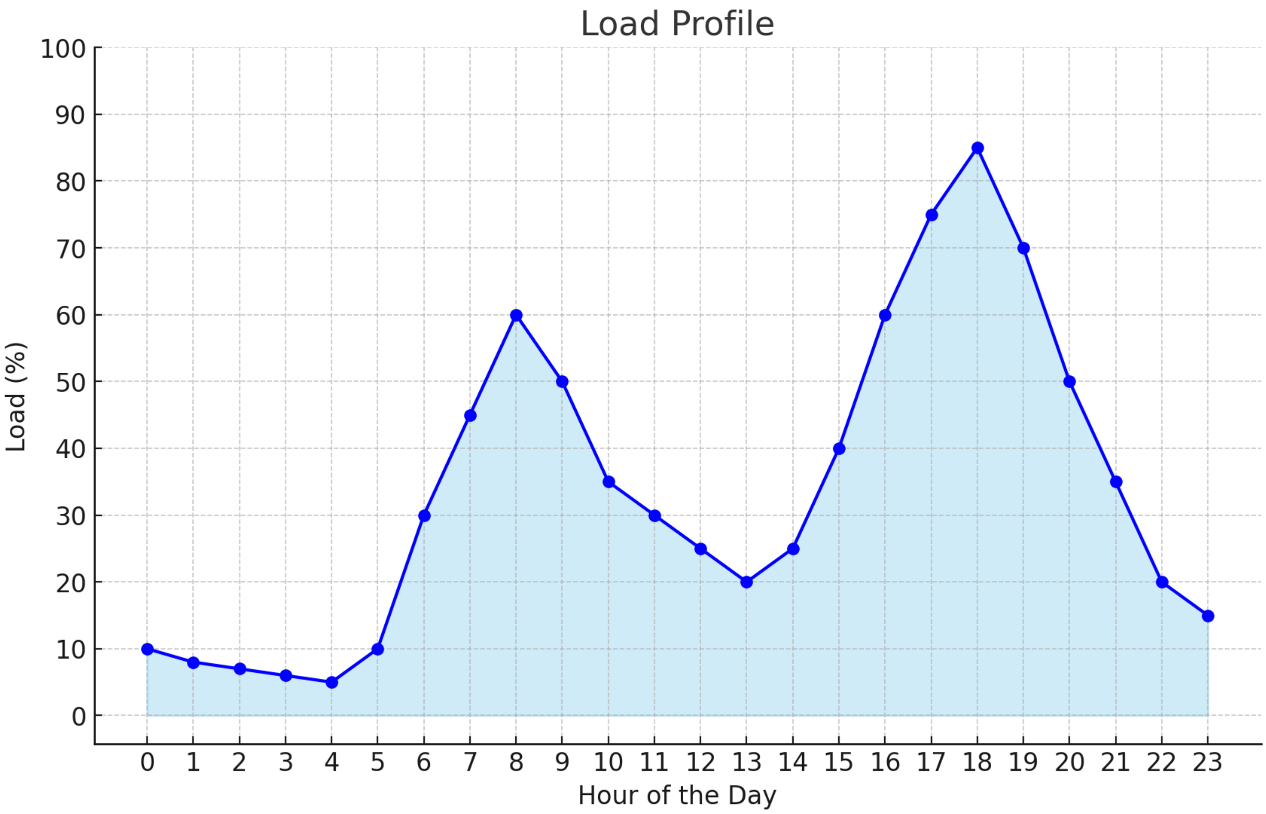

Figure D.1: Typical Load Profile data

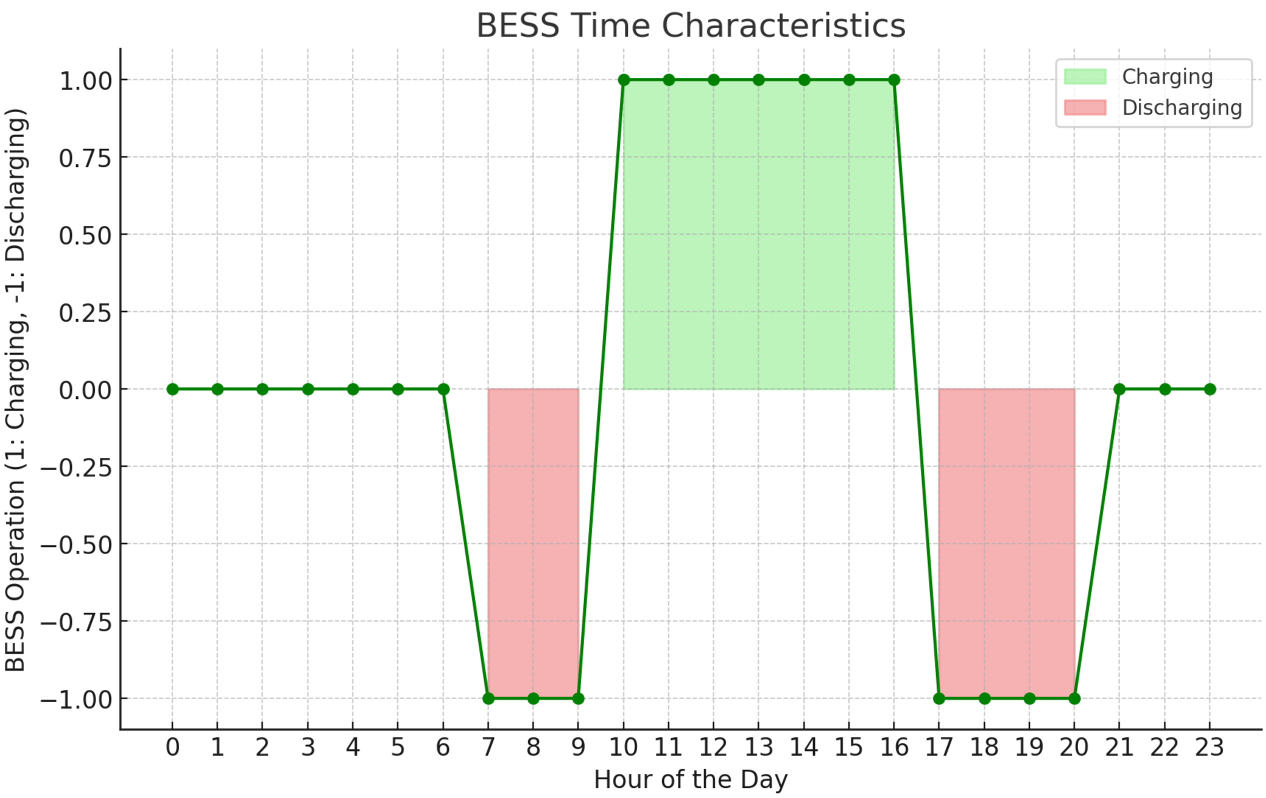

Figure D.2: BESS Time Characteristic