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MODELLING AND SIMULATION OF WIND ENERGY SYSTEMS WITH RESERVES MARGIN IN A DEREGULATED ELECTRICITY MARKET

by

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DECLARATION

I, Siphelele Joseph Mndiya, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

04-SEP-2024

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ABSTRACT

One of the two major uncertainties that a power company must deal with is the potential that the load may be much higher than expected owing to a variety of variables, including weather. On the other hand, utility generation units may experience forced or unexpected outages, reducing the amount of power available overall. Utilities have a reserve margin to take these uncertainties into account. The amount of available but unutilized generating capacity during periods of peak demand is known as the reserve margin. The ideal reserve margin is determined by a load-serving entity's size and composition.

Operating reserve margin from renewable energy sources has been studied in light of the significant increase in the production of electricity from such sources as solar and wind. Although wind energy production has increased dramatically in recent years, much more research is still needed to understand how it might be used to provide operating reserves. This research study highlights the effects of keeping an optimum operating reserve margin on factors such as the stability of the grid. This study also looks at the possibility of using wind energy systems to create active power operating reserve margins taking into consideration their intermittent nature. Owing to the intermittent nature of wind energy, it is also suggested to use a battery energy storage system to provide active power when the wind energy system is limited.

This study makes use of the IEEE 9 bus power system concept, which is modelled using Real-time Simulation Computer-Aided Design (RSCAD), a simulation program. The RSCAD simulation tool is used to model a wind energy system (WES) and a battery energy storage system (BESS), which are then connected to the grid to provide the necessary active power operational reserves. When wind farms are connected to energy storage devices, such as batteries, excess wind energy can be stored for use in high-generation periods and released for use in seasons of high demand or low wind availability. As a result, wind energy is more dependable and contributes more to the reserve margin. Active power control for the involvement of the battery energy storage system and the wind energy system in the provision of active power operational reserves was designed using the RSCAD simulation program.

This study develops an active power control algorithm with a WES and a BESS. Section 5.4, subsection 5.4.1, in Chapter 5 contains the development of the control algorithm. Following the active power control loop's development, Case Studies 1, 2, and 3 were simulated. This study also models, simulates, and analyses the South African power systems network with wind, and battery models with allocated reserve margin. Conduct detailed electricity market investigations with different case studies in the RSCAD software suite for the RTDS simulation package. The result analysis of the simulated case studies shows that the developed active power control loop is effective in restoring grid stability by dispatching the required active power from both the WES and BESS. In deregulated power networks, wind energy systems can efficiently maintain the reserve margin, improving grid stability and reliability and accelerating the shift to cleaner, more sustainable energy sources.

Extensive and systematic literature reviews were conducted, and the theoretical aspects of the topic were also considered. The Real-time digital Simulator Computer-Aided Design (RSCAD) simulation software was used to perform the model and simulations as described in the chapter. The academic and industrial contributions of the research work are highlighted, along with future considerations for advancing the work. Additionally, publications such as journals and conferences are mentioned, and a list of references consulted for this dissertation is included in this thesis.

Keywords: Operating reserve margin, wind energy systems, deregulated electricity market, power quality, battery energy storage system, load demand, contingency reserves, non-event reserves, peak load demand.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDICES

ABBREVIATIONS/ACRONYMS

WES	:	Wind Energy System
BESS	:	Battery Energy Storage System
RSCAD	:	Rea-time Simulator Computer-Aided Design
RTDS	:	Real-Time Digital Simulator
IEEE	:	Institute of Electrical and Electronics Engineers
WTG	:	Wind Turbine Generator
WF	:	Wind Farm
RM	:	Reserve Margin
AGC	:	Automatic Generation Control
PRM	:	Planned Reserve Margin
DERs	:	Distributed Energy Resources
PFR	:	Primary Frequency Response
FERC	:	Federal Energy Regulatory Commission
ISO	:	Independent system operator
RTO	:	Regional Transmission Organisation
WPP	:	Wind Power Plant
JERM	:	Joint Enhanced Reliability Management
GHG	:	Greenhouse Gas
EAF	:	Energy Availability Factor
PV	:	Photovoltaic
IRP	:	Integrated Resource Plan
LOLE	:	Loss of Load Expectation
LOLP	:	Loss of Load Probability
TSO	:	Transmission System Operator
MPC	:	Model Predictive Control
MPPT	:	Maximum Power Point Tracking
FRR	:	Frequency Response Reserve
ENTSO-E	:	European Network of Transmission System Operators

Ni-Cd : Nickel-Cadmium

SOC : State of Charge

IPPs : Independent Power Producers

AVM : Average Value Model

PLL : Phase-Locked Loop

VCO : Voltage-Controlled Oscillator

GLOSSARY

Operating electricity reserves – describes the supply resource capacity that the system operator can use to maintain the supply and demand balance of the bulk electric system for a short period of time.

Reserve margins - the percentage of an electric power system's overall capability that is unused at peak load (for a utility system).

Deregulated electricity market - transmission lines and power plants are owned by market actors other than utility companies. In these situations, electricity is sold by power-generating companies, or generators, into a wholesale market, where retail energy suppliers purchase the electricity and resale it to customers.

Smart grid – an electrical system that reduces costs and preserves the stability and dependability of the grid by utilizing digital technology, sensors, and software to better match the supply and demand of electricity in real-time.

Generation capacity - the maximum amount of electricity that a generator is capable of producing.

Load demand - used to describe the amount of load you see during day-to-day operations.

Grid contingency – an unanticipated breakdown of a single primary component that results in a significant enough shift in the system state to jeopardize grid security.

Induction generator excitation – provision of the required reactive power to start the generator. Induction generator excitation refers to the process of providing a magnetic field to an induction generator, which is a type of electrical generator that uses electromagnetic induction to produce electricity.

Power system stability - refers to a power system's ability to sustain operational equilibrium in normal operating conditions and to bounce back from disruptions to a sufficient degree of balance.

Deregulation - the removal of regulations or restrictions, especially in a particular industry.

Regulating reserves a class of power reserve that is used to continuously adjust the supply and demand of energy, guaranteeing the stability and dependability of the grid. They are employed to control minor, transient variations in the voltage and frequency of the grid.

Following reserves - Following reserves, also known as supplemental reserves, are a type of power reserve used to augment regulating reserves in maintaining grid stability and reliability.

Contingency reserves - Contingency reserves are a type of power reserve used to respond to unexpected and significant disturbances in the power grid.

Ramping reserves - Ramping reserves are a type of power reserve that help manage changes in electricity demand or supply, particularly during periods of rapid ramp-up or ramp-down in grid operations.

Primary reserves - Primary reserves are a type of power reserve that are automatically deployed to maintain grid stability and frequency in real-time.

Secondary reserves - Secondary reserves are a type of power reserve that are deployed to support grid stability and frequency control after primary reserves have responded to an initial disturbance.

Tertiary reserves - Tertiary reserves are a type of power reserve that are deployed to support grid stability and frequency control after secondary reserves have responded to a disturbance.

MATHEMATICAL NOTATIONS AND SYMBOLS

CHAPTER 3

ϕ : Confidence interval
L_{max} : Highest expected load for the control region (in MW)
J : Moment of inertia
ω_0 : Nominal rotor speed
S_N : Apparent power of the generator
H : Inertia constant
ρ : Air density
v : Wind speed
λ : Tip-speed ratio
C_p : Power coefficient of a WT
β : Pitch angle of a WT
R : Radius of the blades
ω_m : Shaft's speed of rotation
T_m : Wind turbine driving torque
J_{eq} : Equivalent inertia of the generator and the turbine
B : Damping coefficient
T_e : Electromagnetic torque of the generator
p : Number of generator pole pairs
ω_m : Rotor's mechanical rotating speed
ω_r : Electrical angular speed
J_V : Virtual shaft inertia
ω_{s0} : Grid synchronous speed
τ_β : Pitch actuator's time constant
T_{cd} : Total time delay
β_{ref} : Reference value for pitch angle
$f_{real}(t)$: Measured frequency at the time instant t
f_{ref} : Reference frequency
$P_{max,bat}$: Maximum rating power of the battery
Δf_{max} : Maximum frequency deviation
k : Shaft's corresponding stiffness constant.

CHAPTER 5

T_T	:	Mechanical torque (N.m) by the WT
P_T	:	Power (MW) by the WT
v_w	:	Velocity of wind (m/s)
ω_{TR}	:	Rotational velocity of the turbine (rad/sec)
v_{kmh}	:	Wind speed (km/h)
v_{ms}	:	Wind speed in meters per second (m/s).
X_m	:	Magnetizing reactance of the induction machine,
f	:	System frequency
L_m	:	Magnetizing inductance of the IG

CHAPTER ONE
INTRODUCTION

1.1 Introduction

There are two major uncertainties facing a load-serving electric power utility. The actual load may be significantly higher than the intended load, owing to a variety of factors including weather. Heavy air conditioning use, for example, increases load during particularly hot summer days. A utility's generation units, on the other hand, may experience forced or unscheduled outages, reducing overall generating availability (Wang & Min, 2020).

A utility keeps a reserve margin to account for those uncertainties. The amount of available generating capacity above peak demand is known as the reserve margin. The size and makeup of a load-serving entity determine the optimal reserve margin (Wang & Min, 2020). Because they manage a large number of generation units and there is little chance of losing many units at once, independent system operators, for instance, may have an optimal reserve margin that is lower than that of a mid-size utility. The optimal reserve margin, on the other hand, is higher for a small utility with only a few generation units, because losing one or two generation units would result in a substantial supply crisis.

There is sufficient reason to look at reserve margin planning for renewable energy given the sharp increase in power generation from renewable sources that has occurred recently on a worldwide scale. Wind power generation has increased dramatically in recent decades, this increase is an advantage because it solves the energy crisis that we are facing especially in South Africa and it can also stabilize climate (Hedayati-Mehdiabadi, et al., 2018). Wind energy is now one of the cheapest renewable energies due to technological advances and lower upfront costs (Hedayati-Mehdiabadi, et al., 2018). The implementation of various emission-reduction initiatives has increased global wind farm installation. China, the US, Germany, and India are the top four nations increasing wind capacity globally (Wang, et al., 2018).

Large utilities controlled all aspects of power generation, transmission, and distribution within their operational boundaries, dominating the electric power market for a long time. Vertically integrated utilities are one type of utility (Karthikeyan, et al., 2013). A power system whereby there is more than just one power producer is based on a restrictionless market structure that includes transactions between energy suppliers and consumers, coordination, and laws that ensure contesting fair open access (Singh & Parida, 2018). Deregulation aims to reduce power costs for consumers while also generating revenue for generating companies, all while maintaining system dependability and security. Energy trading systems help to achieve the goal of a reformed power system, which includes competition and customer choice (Chinmoy, et al., 2019).

This thesis looks at the provision of operating electricity reserves in a deregulated electricity market. This study examines the potential for these operating reserves to be supplied by independent power producers using renewable energy sources, thereby advancing the deregulation of the South African electricity market and fostering competition. The focus of this study is on battery energy storage systems and wind energy systems.

This chapter is divided into the following sections: 1.2 emphasizes the problem's awareness; 1.3 outlines the problem statement; 1.4 explains the research aims and objectives; 1.5 states the hypothesis; 1.6 addresses the delimitation of research; 1.7 conveys the study's motivation; 1.8 outlines the assumptions; 1.9 talks about the methods used to conduct the study; and, finally, section 1.10 closes the chapter.

1.2 Awareness of the problem

South Africa is the largest net electrical generator on the continent and one of the most industrialized, accounting for 45% of the continent's energy output. Eskom uses a range of fuels, including coal, hydro, liquid fuel, nuclear, wind, and pumped storage, to operate 27 main power plants with an installed nominal capacity of over 42000 MW, which provides most of the electricity used in South Africa's nine provinces. South Africa's electrification endeavours, both rural and urban, have been aided by various government policies and programs. As a result, the country's electrification rate has increased from less than 33% in 1990 to 58 percent in 1996 and 90% in 2016 (Monyei & Adewumi, 2017).

In the mid-1990s, South Africa possessed enormous extra energy-producing capacity, with a reserve margin of over 40%. With modest year-to-year changes, electricity demand climbed at a steady 3.5 percent per year, continuing the long-term trend (Trollip, et al., 2014). There was no notable surge in demand that came as a surprise. However, no new capacity was installed as demand soared. As a result, by 2003, the reserve margin had deteriorated to such an extent that supply and demand were severely limited. The bulk energy supply system was becoming increasingly pressured, and there was a growing risk that the 'withdrawal' of system components, such as unplanned power plant or transmission line outages, would compel the system to shed load to maintain system integrity (Davidson & Mwale, 2014).

Even though the system was now operating with an unsustainable reserve margin, there were no clear plans in place to add significant additional generation capacity by 2003. As demand increased, the reserve margin, and hence system reliability, decreased. Appropriate action was not taken, i.e., neither sufficient demand-side measures to lower system load nor sufficient supply capacity improvements were adopted. As a result of a combination of insufficient reserve margin, poor reliability, a stressed system, and system element failures, system demand in the Western Cape surpassed system supply by the end of 2005 (Trollip, et al., 2014).

The load was intentionally halted to maintain system stability, resulting in severe blackouts in the Western Cape. This happened again in early 2006, and by early 2007, the situation had deteriorated, with rolling national load shedding implemented to maintain the integrity of the national energy grid system. Late July 2007, load shedding was required once more. In 2008, the system was significantly pressured, necessitating even more severe load shedding to preserve system stability (Newberry & Eberhard 2007, updated 2008). Aside from rolling load shedding, several significant clients, like as mines and minerals beneficiation plants, had their supply interrupted.

Since the initial load shedding in 2005, there has been a chronic energy supply shortage, necessitating the restriction of supply to major customers to maintain appropriate reserve and a period of national load shedding. Short-term surges in demand, such as those produced by cold weather, or short-term supply problems, such as coal availability to one or two power plants, events that a system with appropriate reserve margin would be able to absorb, constitute a constant danger to system security (van der Heijden, 2013).

Progress on system extensions has been slowed, thus the generation shortage is unlikely to be remedied for several years. Electricity shortages and/or an insufficient reserve margin are possible for a very long time and there is no viable solution in place currently. The South African electricity is still far from being deregulated.

1.3 Research problem

The research problem addressed in the project as follows:

- Insufficient reserve margin: There are currently no reserve margins available in South Africa. As a result, an increase in load demand or a generating plant failure requires the power company to adopt load shedding, which has negative consequences for consumers and companies.

- Insufficient storage capacity: South Africa lacks sufficient storage capacity. The excess electricity generated is not stored anywhere so that it can be used in times of need, such as during peak demand hours.
- High cost of electricity: The cost of power in South Africa continues to rise. The poor are most affected, as they can no longer utilize electricity whenever they need it because they cannot pay for it.
- Generation capacity and demand are not aligned: This problem is resulting in a lack of efficient tariffs. The tariff will rise if demand does not keep up with the growing generation capacity.
- High system losses: Energy loss occurs naturally in electricity networks between generation and consumption. The distance between generation and consumption plays a huge role in system losses.

Research problem statement: To explore, design, and implement active power regulation methods for wind and battery energy storage systems (BESS) to integrate these systems into the grid and offer operating reserves for electricity in a deregulated market.

1.4 Research aims and objectives

Aim of the research project is to efficiently maintain the reserve margin in deregulated power systems, improve grid stability and reliability, and encourage the shift to a cleaner, more sustainable energy future, the research looks into wind energy systems in conjunction with BESS.

The goal of this study is to look at South Africa's electrical reserves margin and storage capacity. Then, to improve the power market, model, simulate, and analyze a wind energy system with reserve capacity.
A list of Objectives outlining how the aim is achieved is provided below:

- Research investigation on the literature review on operating energy reserve and its price benefits
- Study literature review on power quality benefits with reserve margin.
- Analysis of South African operating reserve methodology and its implementation.
- Study the theory on energy reserve and its methods adopted nationally and globally.
- Develop an active power control algorithm with a WES and a BESS. Section 5.4, subsection 5.4.1, in Chapter 5 contains the development of the control algorithm.

- Model, simulate, and analyze the South African power systems network with wind, and battery models with allocated reserve margin. Conduct detailed electricity market investigations with different case studies in the RSCAD software suite for the RTDS simulation package.
- Simulation study of different case studies which includes the varying wind speed and battery storage capacity. Three case studies were simulated in Chapter 5 under section 5.5.

1.5 Hypothesis

It is hypothesised that,

- Wind energy systems will improve South Africa's current reserve margin.
- By combining battery energy storage systems with wind energy systems, there will always be adequate power for the reserve margin, even if the wind systems are not working optimally owing to variabilities due to weather.
- The combination of wind energy systems with battery energy storage systems for reserve margin will improve the electricity market in South Africa.

1.6 Delimitations of the research

The following are the delimitations of this research project,

- This research study will focus only on wind power systems as a sustainable energy source and will not consider other sustainable energy sources like solar, hydro, etc.
- This research is based on a large-scale wind power plant with capacity of 48 MW.
- The WES uses a type 2 induction generator wind turbine rated at 4 MW power output. When the WES is integrated into the grid, the efficiency of each WT drops, and the power output is limited to 3.68 MW.
- This research will only look at BESS as an ES technology and will not look at alternative options.
- This research focuses on the Lithium-ion battery technology and the BESS is modelled as a large-scale system. Due to the size of the batteries, charging can take longer.
- This research study uses a modified IEEE 9 bus power system network to simulate grid contingencies and to test the effectiveness of the active power dispatch control loops.
- There are different types of operating active power reserves mentioned in this study, but this research focuses mostly on regulating reserves. The following reserves cannot be investigated as they require manual dispatch whereas the developed active power algorithm is automatic. The reserves falling under event

reserves, contingency and ramping reserves, cannot be investigated in this study as they are on dispatched during grid events and all case studies simulated in this study cannot be categorized as events.

1.7 The motivation of the research problem

This research will benefit the institution and the South African power utility, ESKOM, as it is meant to identify the current shortfall of the electricity reserve margin and the storage capacity in South Africa. This research will find a way to determine the amount of operating reserve margin that is needed taking into consideration the peak demand and will also provide price and power quality benefits associated with keeping optimum operating reserve margin. The intention is to implement wind energy systems together with battery energy storage systems to provide optimum operating reserve margin.

Grid Stability and Reliability: Wind energy generation can be variable due to fluctuations in wind speed. When wind farms are connected to BESS, excess energy can be stored for times when wind output is strongest and released for times when it isn't, resulting in a more steady and dependable power supply. This stability contributes to meeting reserve margin requirements, which are essential for maintaining grid reliability.

Fast Response Time: BESS has the capability for rapid response times, enabling them to quickly inject stored energy into the grid when needed. This agility is critical for supporting the reserve margin by providing rapid adjustments to fluctuations in demand or unexpected generation outages.

Mitigating Intermittency: Wind energy's intermittency can pose challenges for grid operators in meeting reserve requirements. In order to mitigate the intermittent nature of wind power and guarantee a steadier supply of electricity, BESS can mitigate these oscillations by storing energy during quiet times and releasing extra energy during high wind generating periods.

Optimizing Renewable Energy Integration: Integrating wind energy with BESS allows for better utilization of renewable resources. When wind generation is minimal or during peak demand, excess energy produced during off-peak hours can be stored in batteries and used. This optimization maximizes the contribution of wind energy to meeting reserve margin requirements while minimizing reliance on fossil fuel-based generation.

Reducing Curtailment: In certain instances, wind farms could have to reduce their output due to inadequate demand or transmission capacity. BESS provides an alternative outlet for excess wind energy, allowing it to be stored rather than wasted. By reducing curtailment, wind energy paired with BESS can more effectively contribute to meeting reserve margin targets.

Economic Benefits: Integrating wind energy with BESS can provide economic benefits by allowing wind farms to participate in ancillary service markets and other revenue streams. By monetizing their ability to support the reserve margin, wind energy projects can improve their financial viability and attract investment, ultimately driving further deployment of renewable energy resources.

1.8 Assumptions

Based on research conducted thus far, the following assumptions have been established:

- The IEEE 9 bus system used in this research provides a simplified representation, making it easier to simulate and analyse. It is a flexible system that can be modified to represent different power system configurations and scenarios. It is also using well-defined and widely accepted parameters, making it a common reference point.
- The WES is the main active power compensator, due to its intermittency and other issues like outages, the battery energy storage system will also provide active power should the WES not be able to provide the total active power required by the grid.
- Active power control techniques must be put in place to integrate wind energy systems and battery energy storage systems into the grid without collapsing it.
- The developed active power control loop must successfully stabilize the frequency with 49.5Hz and 50.5Hz as per the grid code requirements (Eskom, 2015).
- Simulating wind power systems and evaluating their integration into the grid with the aid of RTDS, helping engineers design and optimize wind power projects while ensuring grid stability and reliability.
- The assumption is that the operating reserve margin should be 15% of the peak load demand.

1.9 Research design and methodology

The purpose of this project is to develop and put into practice an active power regulation technology that will make it easier to integrate battery energy storage and wind energy systems into the grid and provide electricity for operational reserve margin in a deregulated electricity market. This research investigates the potential of wind power systems in the provision of operating reserves. Wind power systems are known for their intermittent nature, which means that they be trusted to be reliable on their own as operating reserves are required in unplanned or emergency grid situations. A BESS is used to store electricity during times of high wind speed and low demand and to discharge during times of high demand and low wind speed in order to solve the intermittent nature of wind power.

It is possible to achieve the aforementioned goals with the existing advanced technologies available through Real Time Digital Simulation. To achieve the study's goal, research methods including a literature review, theoretical framework, modeling and simulations, and documentation procedures are employed. Figure 1.1 depicts the framework of the research approach used in this study.

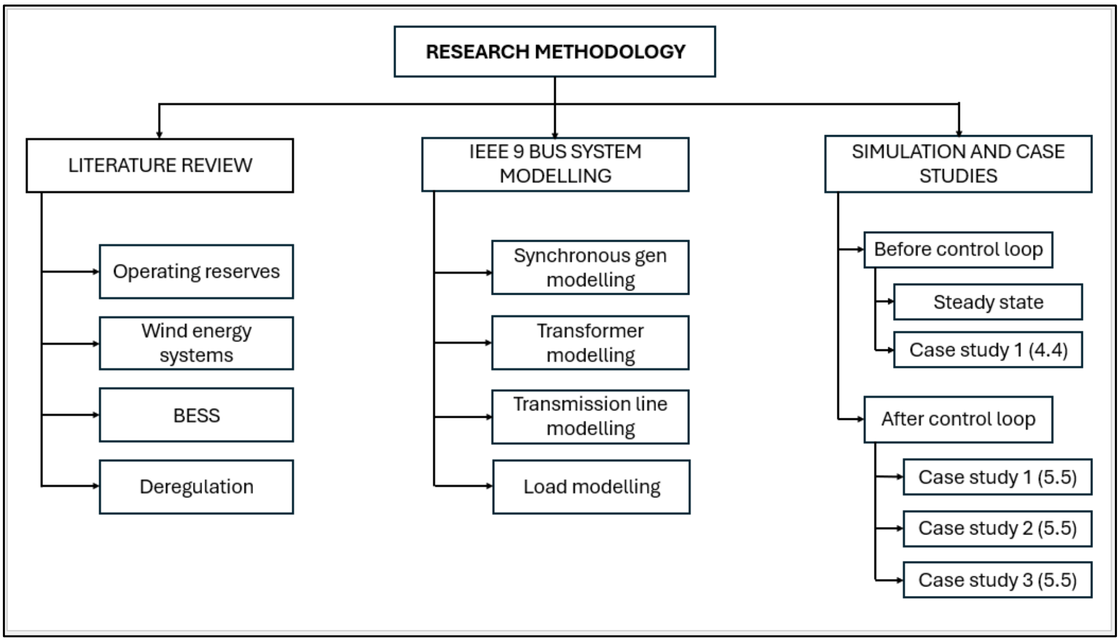

Figure 1.1: **Research Methodology structure**

1.9.1 Literature review

There is a lot of literature that has been published about operating reserves. The literature also exists about the provision of these reserves using renewable resources. The literature related to wind power plants and battery energy storage systems providing operating reserves is collected by reading recently published journals and books, and information from the internet, accompanied by discussions with experts in this field.

1.9.1.1 Operating reserves

Traditionally, the operating reserves have always been provided using traditional power generation methods such as fossil fuels. The recently published literature on operating reserves looks at the potential and the role that can be played by renewable energy resources like wind and solar in the provision of operating reserves.

According to the published literature, there are different types of operating reserves. In the literature review chapter (chapter 2, section 2.2), the types of reserves are explored.

1.9.1.2 Wind energy systems

Wind energy systems are known to be intermittent, and they introduce new challenges when integrated into the grid. A thorough literature review will be carried out to understand the kind of challenges that come with the integration of wind energy systems into the grid. A review will also be done to determine the types of operating reserves that can be provided using wind energy systems. Different control methods that can be implemented to get the best out of wind energy systems in the provision of operating reserves will be looked at.

1.9.1.3 Battery Energy Storage Systems

The energy storage systems field is another well-researched area. In published literature, different types of energy storage systems are explained. This research focuses on battery energy storage systems.

In Chapter 2, the literature on different types of battery energy storage systems will be studied. The literature focuses on the operation of these different energy storage systems and their advantages and disadvantages. Other publishers have looked at how battery energy storage systems can help in the provision of operating reserves. Some studies have gone further to determine the types of operating reserves that are possible to provide using battery energy storage systems. The intention of the literature reserve will also be to find out about different control methods that can be implemented to get the best of the battery energy system in the provision of operating reserves.

1.9.2 Modelling and Simulation

The IEEE 9 bus power system network is used in this investigation. The stability and precision of the experimental results are guaranteed by the utilization of this system. This system will be modified to suite some requirements of the South African power system standards, like for example the system frequency of 5oHz. The decision to use and modify the IEEE 9 bus system was taken to have a controllable network model and also because the simulation packages that are going to be used do not have enough processors to simulate a bigger network.

This research study uses the RSCAD simulation package to model and modify the IEEE 9 bus system. The network's response to various scenarios, such as an increase in load demand, the loss of a transmission line, or the loss of a generator, will be simulated to see how the voltage and frequency change.

Once it has been established in RSCAD that sudden changes to the load demand and available generation impact the continuity and quality of supply, that will motivate the need for operating reserves in the network. Through the mathematical formulas found in published literature, the required optimum operating reserve margin will be determined. To ensure supply security, especially during times of high demand, Eskom states that the operating reserve margin should be 15% of the peak load demand and must be maintained at that level as the demand for power rises (Eskom, 2015).

The output power of the wind energy system will be known once the necessary operating reserve has been computed. The estimated operating reserves must come from the wind energy system. RSCAD or RTDS will be used to model the wind energy system in conjunction with the battery energy storage system. RTDS will be used to implement control strategies for the battery energy storage system and the wind energy system. A variety of case studies will be replicated both before and after the proposed control procedures are put into practice.

1.9.3 Documentation method

The following bullets list and describe the six chapters and appendices that make up the thesis document.

- **Chapter 1:** The introduction of the study, a description of the problem, and a hypothesis.
- **Chapter 2:** The literature review of the existing publications about operating reserves and their provision from wind energy systems in a deregulated electricity market.
- **Chapter 3:** Theory of operating reserves, wind energy systems, battery energy storage systems, and electricity deregulation.
- **Chapter 4:** Simulation and modelling studies of the modified IEEE 9 bus power system.
- **Chapter 5:** Modelling of wind energy systems and battery energy storage systems and their respective control techniques and case studies.
- **Chapter 6:** Conclusions and recommendations.

- **Appendices:** Significant attachments, namely figures plant sub-components modelling from the body of the thesis documents, modelling parameters, and some results.

1.10 Conclusion

There are two major uncertainties in electric power utility. The actual load may be significantly higher than the intended load, owing to a variety of factors including weather. A utility's generation units, on the other hand, may experience forced or unscheduled outages, reducing overall power supply (Wang & Min, 2020). These major uncertainties are the reason why we need an electricity reserves margin so that when these unforeseen circumstances take place, utilities will still be able to continue supplying power to their customers without any issues.

This research study proposes wind energy systems integrated with battery energy storage technologies as a way of securing electricity reserves. This study proposes a deregulated electricity market meaning that the wind energy systems do not necessarily have to belong to the main power utility. When independent power producers are involved, the price of electricity gets affected and that is one of the factors that this study is trying to explore.

The following chapter examines the literature on wind power plants with BESS supporting the operating reserve margin that may be found in journals, conference papers, and books.

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CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Electrical power utilities are facing two major uncertainties. The first uncertainty is that the actual load demand may be higher than the nominal load and this can be due to a variety of factors including a change in weather. Secondly, the generating units of a power utility may face forced or unscheduled outages which reduces the overall power supply. Power utilities need to keep an electricity reserve margin to account for the uncertainties mentioned above. The quantity of generating size that is available above the highest electrical power demand is known as the reserve margin (Wang & Min, 2020).

The amount of power generated by sustainable energy sources is rapidly increasing on a global scale. The production of wind power has grown significantly in recent decades; this growth is advantageous since it addresses the energy problem that we are currently experiencing, particularly in South Africa, and it can help stabilize the environment. Wind energy is now one of the cheapest renewable energies due to technological advances and lower upfront costs. The implementation of various emission-reduction initiatives has increased global wind farm installation (Hedayati-Mehdiabadi, et al., 2018).

Big utilities have traditionally dominated the electric power industry because they have control over all power production, transmission, and distribution activities within their service region. A power system whereby there is more than just one power producer is based on a restrictionless market structure that includes transactions between energy suppliers and consumers, coordination, and laws that ensure contesting fair open access. Deregulation aims to reduce power costs for consumers while also generating revenue for generating companies, all while maintaining system dependability and security (Karthikeyan, et al., 2013) (Singh & Parida, 2018) (Chinmoy, et al., 2019).

The impact of growing wind penetration on operating reserve margin scheduling in a deregulated market is the main topic of this chapter. Several articles have been reviewed to identify and assess different types of techniques and methodologies that have been used by different researchers to model and determine the operating reserve margin taking into consideration the intermittency nature of wind energy. This literature review also analyses published articles about the provision of operating reserves in a deregulated market, with the focus being on how this can affect the price of electricity. This chapter goes over the function that energy storage devices may play in demonstrating the operational reserve margin in a deregulated electricity market while taking into account the erratic nature of wind. Last but not least, this chapter examines the electricity reserve margin and storage capacity in South Africa.

In this chapter, section 2.2 highlights the literature related to operating reserves, section 2.3 describes the literature related to wind energy systems with operating reserves, section 2.4 outlines the literature related to the role of battery energy storage systems in reserve provision, section 2.5 discusses the literature related to operating reserves in a deregulated market, section 2.6 discusses the electricity reserve margin and energy storage capacity in South Africa, section 2.7 provides a comparison of research on optimum operating reserves, section 2.8 produces a comparison of existing papers on wind energy systems with operating reserve, section 2.9 provides remarks and observations from the literature review and lastly, section 2.10 concludes the chapter. The organization of the chapter on literature review is depicted in the graphic below, Figure 2.1.

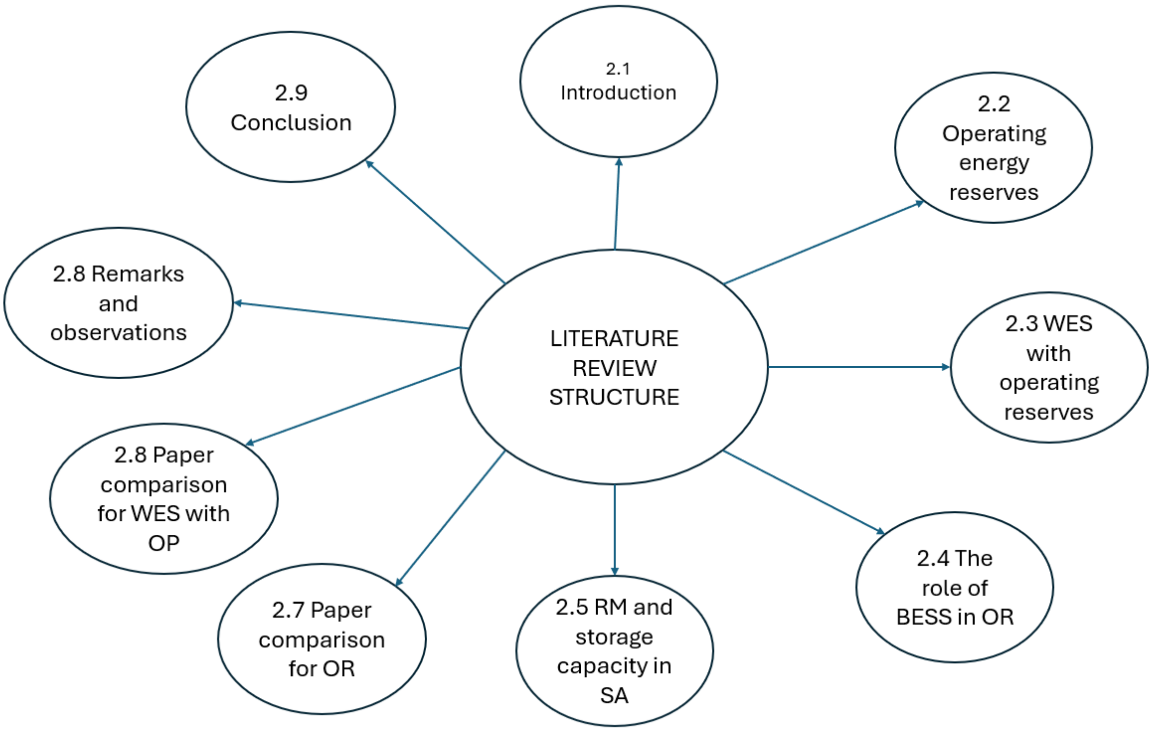


Figure 2.1: Literature review framework

2.2 Operating energy reserves

Reserve margin can be explained as the amount of energy that is stored somewhere to help just in case there is a situation whereby the load demand is greater than the available generating capacity, this can be due to certain issues including inaccurately forecasted electricity demand or unpredicted generator failures. The reserve margin can be further classified as operational, supply, or facility based on how it will be dispatched and the amount of energy that is stored (Lee & Cho, 2022).

The excess electricity that can be used when all of the nation's power-producing facilities are operating at full capacity is known as the facility reserve margin. The supply reserve category can be defined as the total amount of excess power generated by the facilities that are currently operational. The standby margin that can be obtained and used within a limited window of time (60 to 120 minutes) following the demand response is what is meant by the operational reserve category. To put it another way, the operating reserve margin is used to deal with sudden changes in load, adjusting the frequency of the system, and unplanned but transient failures (Lee & Cho, 2022).

Power system functioning depends heavily on operating reserves since massively unknown events can happen at any time and disrupt system balancing. According to reaction delay, operating reserves are often divided into regulation, spinning reserve, and nonsynchronous reserve. Automatic generation control (AGC) typically deploys regulation, also known as frequency response, every 3-5 seconds to maintain system frequency within a narrow range of the nominal frequency. The governor increases the generator's real power output when the frequency deviates below a predetermined threshold from its nominal value, and vice versa. Spinning reserves are short-notice, often within a 10-minute window, online generation capacities. These generators can be dispatched within their capacity and ramp rates and already operate at the synchronized frequency. Nonsynchronous reserves are units that are offline and respond after 10 to 60 minutes. These three types of reserves can be viewed as insurance for the power system performance, lowering the risk of unforeseen events, load fluctuation, intermittent renewable energy, etc (Tao, 2015).

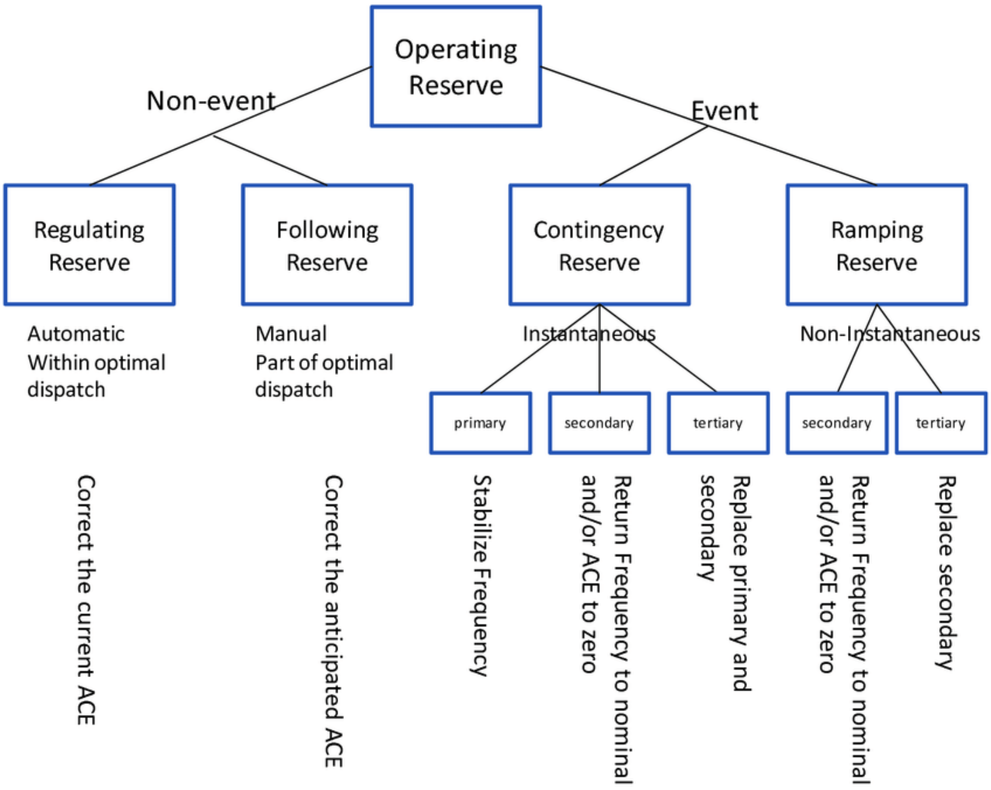


Figure 2.2: **Examples of operating reserve categories and how they are related (Ela, et al., 2011)**

The production of wind energy is erratic and unpredictable. Determining the comparable operating reserve is the system operator's primary concern in power systems with a drastic increase in the introduction of wind power. Afshar and Shokri Gazafroudi (2013) suggest a stochastic programming approach to predict operational reserves in simultaneous market clearing of energy and reserve based on scenarios produced by Monte Carlo simulation. This model covers the cost of unintentional load shedding and wind leakage and takes wind power, load, and network uncertainty into account. To assess the suggested methodology for analyzing the varied effects of wind energy output on system operating costs and reserves, examples and case studies are employed.

An enhanced probabilistic model was presented by (Rejc and Čepin, 2014) to determine the additional operational reserve in power networks that have installed renewable energy sources. Their approach to assessing the dependability of power systems is remarkable since they consider both the age of the producing units and the fluctuating production of renewable energy sources. They found that the availability of producing units and the energy provided by renewable sources, both of which are impacted by age and frequent cause failures, determine how much additional operational reserve is needed (Rejc & Čepin, 2014).

(You et al., 2017) provided a phase-by-phase optimal energy and operational reserve schedule for the day ahead and throughout the day to solve the difficulty of integrating wind generation into the conventional power system. The configuration for operational reserve and producing output may be adjusted continually to control the power system's performance when prediction errors for wind power and loads decrease from long-term to short-term. The power system's capacity to absorb wind energy has purportedly risen, and operation is now more economically effective, according to numerical findings of the advised energy and operational reserve scheduling approach (You, et al., 2017).

(Bapin et al., 2018) suggested a probabilistic strategy for the assessment of operational reserve capacity in linked power networks, taking into consideration demand and renewable power prediction errors, reserve scheduling costs, and other variables. The IEEE Two Area Reliability Test System was used to evaluate the recommended course of action. The main dependability metrics are contrasted with those derived from the deterministic and probabilistic methods, which overlook inter-zonal interactions. The recommended method results in the lowest operational reserve costs as compared to earlier methods (Bapin, et al., 2018).

To determine optimal reserve margins, (Wang & Min, 2020) systematically reviews reliability metrics and further investigate how to determine optimal reserve margins based on those metrics for the electric power industry. The authors present an industry-standard approach and economic approach to determine optimal reserve margins.

Grid operators have evolved strategies over time for containing the fluctuation and uncertainty of conventional generation and demand in a system. The scheduling and dimensioning of reserves allow for the coverage of a wide range of circumstances. A variety of periods are considered while allocating reserves, and different reserves will be available to restore system stability after an incident. Because reserves are activated and used in response to system requirements, it is not always clear which reserved category is being used during real-time operation. Reserves are purchased in accordance with the Holttinen et al. (2013) distribution of reserves research. While some reserve types can be acquired through competitive bidding processes or open markets, others can necessitate the purchase of generator services in order to meet grid requirements (Holttinen, et al., 2013).

According to (Diewvilai, et al., 2011), as indicated in the equation below, the amount of reserve margin can be deterministically determined in percentage of peak demand:

$$RM = \frac{IC - Peak\ Load}{Peak\ Load} \cdot 100 \qquad (2.1)$$

where RM is the percentage reserve margin and IC is the total installed capacity.

In a paper authored by (Chuang, et al., 2019), the percent reserve margin (PRM) is determined as follows:

$$PRM = \frac{Power\ Supply - Power\ Demand}{Power\ Demand} \cdot 100\% \qquad (2.2)$$

The planning reserve margin PRM was defined by Lin et al. in research from 2018 as the percentage of available generating capacity G above peak demand P during an annual peak demand period (Lin, et al., 2018):

$$PRM = \frac{G - P}{P} \qquad (2.3)$$

The equations used by the three different authors mentioned above are very similar. The key aspect when determining seems to be the peak load/demand. An interesting this to notice is that (Diewvilai, et al., 2011) use installed capacity to determine the reserve margin whereas (Lin, et al., 2018) use available generating capacity.

2.2.1 Review discussion on Operating energy reserves

There are different types of operating reserves mentioned in this chapter such as regulating reserves, following reserves, contingency reserves, and ramping reserves as shown in Figure 2.2 above. As mentioned in the delimitation in section 1.6 of chapter 1, this thesis focuses on only the regulating reserves. The developed active power control algorithm operates automatically which means it cannot be used to practically investigate the following reserves as they require manual operating. The contingency reserves and the ramping reserves are classified as abnormal even reserves and they cannot be practically investigated in this study as all the case studies simulated in this research will not include any abnormal grid events. Regulating reserves are investigated practically in this study as they require automatic operating and have a main aim of balancing the supply and demand which is also the main aim of the developed active power control algorithm. The regulating reserve is adopted and validated using simulation in Chapter 5, section 5.5.

The table below, Table 2.1, highlights some research gaps with their definitions of operating reserves which were identified during the literature review. The table also provides brief summary on how these research gaps are addressed in this thesis.

Table 2.1: **Review of gaps on operating energy reserves & how those are addressed in this research thesis**

Research gap	Definition	How does this thesis address the gap?
Optimal reserve sizing	Determining the optimal amount of reserves needed to balance supply and demand while minimizing costs.	This study adopts an Eskom standard which states that the operating reserves should be at least 15% of the peak load demand (Eskom, 2015).
Integration with renewables	Investigating how to effectively incorporate renewable energy sources into reserve management.	This study investigates how can wind energy systems be effectively incorporated in the provision of operating reserves.
Grid resilience	Enhancing reserve management to address extreme weather events.	One of the simulated case studies in this study mimics a condition of a load demand increase which can be due to extreme weather events. The developed active power control algorithm addresses this.
Distributed energy resources (DERs)	Investigating how distributed energy resources (DERs) contribute to the provision of operating reserves.	This study investigates the function of specifically wind power systems in operating reserve provision.
Emerging Technologies	Exploring the potential of new technologies like energy storage and demand response in operating reserves.	This study explores the potential of BESS in operating reserves with Lithium-ion batteries being the preferred technology.

2.3 Wind energy systems with operating reserves

Studies into the integration challenges these sources present have been sparked by the grid's recent, steady expansion of renewable, variable energy sources. As of 2016, there were 470 GW of installed wind capacity worldwide. The availability and generation constraints of variable generators like wind and solar facilities are inherently limited. The current wind speed affects the output of wind turbines, also, solar power plants cannot produce electricity at night when there is no light intensity from the sun. It is impossible to accurately forecast the output of these generators in advance. When variable generators are used to supply a sizable amount of a region's electrical energy needs, new regulations are required to handle possible issues (Rebello, et al., 2019).

Variable generators have replaced some traditional generators like coal- or gas-powered generators, which has led to some of these issues. These traditional generators offer more grid functions in addition to energy. Ancillary services are the collective term for all of them. Although there isn't a single definition that fits all circumstances, examples of auxiliary services include operating reserves, ramping reserves, damping, reactive power support, primary and secondary frequency response, and so on. Variable generators are replacing conventional generators; thus, it has been investigated whether they could offer some of these additional services (Rebello, et al., 2019).

In the event of unanticipated occurrences like generator failure and load changes, the operating reserve is the generator capacity that is immediately accessible for a brief period to create a real-time balance between supply and demand. The maximum capacity of an online generator or a predetermined proportion of the load is typically used to calculate the reserve capacity for load variations (for generator failure) (Sedighizadeh, et al., 2019). There are uncertainties when large-scale renewables are integrated into the electricity system because of the source's intrinsic volatility and the difficulty in precisely forecasting output. to balance the power, a sizeable additional reserve capacity must be installed, either upward or downward. The use of a fair reserve determination technique is crucial for the system to run profitably and securely, as well as to enable flexible regulation-related service pricing (Sedighizadeh, et al., 2019). If there is insufficient reserve, wind power generation may be reduced or load-shifted, and if there is too much reserve, system operation may become less economically efficient (Sedighizadeh, et al., 2019).

2.3.1 Reserve provision with wind energy systems

There have been some attempts at conducting research into how renewable generation can contribute to the provision of reserves now that large-scale wind power has been incorporated into the grid, but these efforts have been constrained by the stochastic and intermittent nature of renewable generation. Additionally, wind power generation typically uses a reloading technique to offer reserves, which inevitably results in large wind energy loss. A detailed trading mechanism addressing this mode must be created in the power market to make up for idle producing capacity (Huang, et al., 2020).

Regarding the integration of large-scale wind power, there are two linkages related to reserve determination that have not yet been thoroughly described: (1) The relationship between the operational reserve needs and the extent of integration of wind power; and (2) The relationship between the operational reserve requirement and the level of wind power uncertainty (Huang, et al., 2020). Due to the considerable differences in wind power generation, the network power flow may also fluctuate, increasing the risk of failure for generators that are frequently adjusted to lessen volatility. So, it's crucial to take the network limitations (i.e., the demand for the scheduling plan following unpredictable occurrences to satisfy the network requirements) and the N-1 generator failure into account when determining the reserve capacity for wind power (Huang, et al., 2020).

Wind used to be viewed as a non-dispatchable "must-take" resource without the capacity to offer reserves, however, it is now understood that a wind turbine's production may be precisely controlled (up to the amount allowed by instantaneous wind speed). As a result, wind can offer various reserve services. Of course, there are significant distinctions between wind and more conventional resources that offer both relative benefits and drawbacks (Denholm, et al., 2019).

2.3.2 Frequency response with wind energy systems

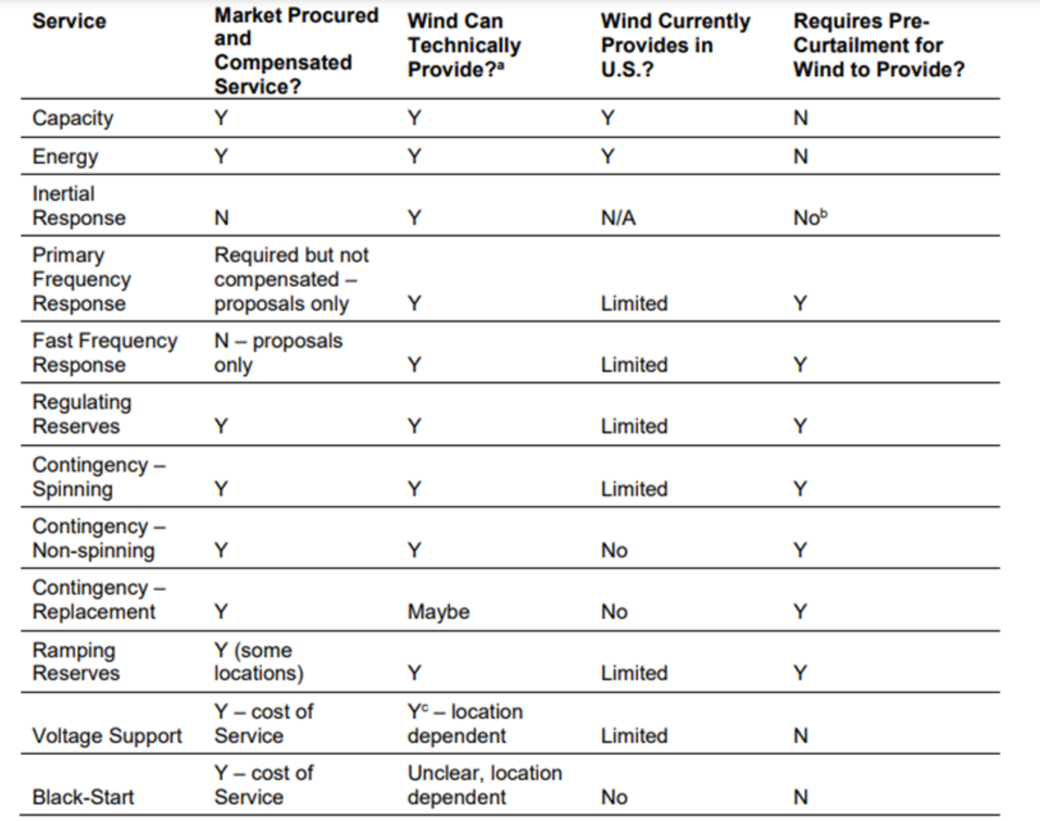
Current sources of frequency-responsive reserves are 1) The rotating mass of synchronous generators' intrinsic physical inertia and 2) The main frequency responsiveness. The Federal Energy Regulatory Commission (FERC) mandates that new wind turbines deliver primary frequency response (PFR) since wind generators have proven they can provide both an "inertia-like" product and it (FERC 2018c). The increased use of wind (and Solar) has also prompted researchers to look more closely at alternate frequency response solutions that are more appropriate for a time when inverter-based machines will predominate. Modern wind turbines do not generate inertia in the traditional sense since they do not use synchronous generators (defined as automatically resisting changes in frequency). Yet, the rotating mass of a wind turbine's generator, shaft, and blades contains kinetic energy that may be harnessed and used to add actual electricity to the grid quickly. To provide inertial service in this way, active grid frequency monitoring is necessary since the generator must be configured to increase output above what "steady state" wind speeds can support. This momentary action will decelerate the turbine. Nonetheless, it has the potential to postpone frequency decay long enough for other systems, such as primary frequency response, to step in and help with frequency restoration (Denholm, et al., 2019).

2.3.3 Grid services with wind energy systems

A synchronized generator must be able to alter its output in response to a signal from the system operator to serve as a regulating reserve. Wind power plants can develop regulatory reserves because they have the speed and duration needed to do so, but they must be limited first to produce upward reserves (Denholm, et al., 2019). Due to this requirement, wind energy has primarily been used to supply regulating reserves, with Xcel Energy in Colorado serving as one example. Regulating reserves are normally the most expensive reserve product; hence, it is anticipated that wind will offer the "first" market reserve commodity that is frequently needed. Rules regarding wind-based regulatory reserves in U.S. independent system operator/ regional transmission organization (ISO/RTO) markets are hazy, contradictory, and changing (Denholm, et al., 2019).

Spinning contingency reserves typically need to be able to: synchronize with the grid and start responding rapidly (within a few seconds); reach a setpoint in around 10 minutes; and hold output for at least 30 minutes (60 in a few locations). Criteria 1 and 2 are technically feasible for pre-curtailed wind, but the third criterion may present a higher technical challenge due to the greater fluctuation and less predictable nature of wind over longer timeframes. There is no motivation for wind to provide this service because contingency reserve prices are often lower than those of regulation, and market restrictions have restricted public discussion of wind providing it (Denholm, et al., 2019).

The grid services that wind energy plants are capable of offering are summarized in Figure 2.3. The availability of the wind resource in terms of time and place limits wind's potential to technically offer almost all of the services purchased and used in the grid, according to both current practices and continuing research. Due to market regulations, the aforementioned limitations, and economic concerns, wind does not now supply all services in all U.S. locations, despite its technical potential. The relative costs or values of the various services, the competition from other suppliers, and the opportunity costs brought on by the fact that the majority of reserves call for pre-curtailment are all considered economic factors. Wind energy will probably continue to serve as the main source of energy until there is a big reduction in it.



Service	Market Procured and Compensated Service?	Wind Can Technically Provide?[a]	Wind Currently Provides in U.S.?	Requires Pre-Curtailment for Wind to Provide?
Capacity	Y	Y	Y	N
Energy	Y	Y	Y	N
Inertial Response	N	Y	N/A	No[b]
Primary Frequency Response	Required but not compensated – proposals only	Y	Limited	Y
Fast Frequency Response	N – proposals only	Y	Limited	Y
Regulating Reserves	Y	Y	Limited	Y
Contingency – Spinning	Y	Y	Limited	Y
Contingency – Non-spinning	Y	Y	No	Y
Contingency – Replacement	Y	Maybe	No	Y
Ramping Reserves	Y (some locations)	Y	Limited	Y
Voltage Support	Y – cost of Service	Y[c] – location dependent	Limited	N
Black-Start	Y – cost of Service	Unclear, location dependent	No	N

Figure 2.3: **Grid Services and Provision from Wind (Denholm, et al., 2019)**

With pollution reductions and the availability of fuel at no cost, the expansion of wind power as a source of electrical energy has brought many major advantages. In addition, it has made operating power systems more difficult due to the greater fluctuation and uncertainty it has brought about. The amount of various sorts of reserves carried is calculated using several assumptions and procedures, which are described in detail in (Ela, et al., 2010), as well as how these methodologies have evolved as more studies has been done (Ela, et al., 2010).

2.3.4 Strategies to determine reserve margin with wind energy systems

The approaches utilized in recent wind integration evaluations and operating practices were described in 2013 (Holttinen, et al., 2013), along with major findings that contrast various methods or data. The reserve impact of wind energy can be determined using a variety of approaches. The adoption of dynamic approaches—which take into account certain system states to reduce overscheduling of reserves—has been seen to be a common trend. Dynamic approaches can be deterministic or probabilistic; nevertheless, deterministic procedures may be somewhat dependent on statistical variations in the wind and load and hence include a probabilistic component. Some options make use of more complex probabilistic techniques, including computing dynamic LOLP values to determine a reserve level that keeps the risk constant (Holttinen, et al., 2013).

In research from 2014 (Zhou & Botterud, 2014), which also offers a probabilistic technique to estimate the curve, the demand curve for operational reserves represents the price that a system operator is willing to pay for these services. The cost of wasted energy and the projected loss of load is taken into account when calculating the demand curve, along with the uncertainty caused by generator contingencies, inaccurate load forecasts, and inaccurate wind power forecasts. The strategy focuses on improving scarcity pricing and more effectively integrating wind energy, which are two significant challenges with the structure of the electricity market (Zhou & Botterud, 2014).

The financial benefits of a probabilistic-dynamic method compared to more traditional quantification approaches in power networks with significant levels of wind power penetration were examined in 2016 research (Rahmann, et al., 2016). The method accounts for the volatility and unpredictability of load and wind predictions as well as regular generator outages. The technique determines the amount of operating reserves for the forthcoming hour that minimizes the overall cost of the power system by adding up the operational costs and the societal costs related to the costs of the projected energy not delivered. The authors use the Chilean power system as an example to demonstrate the efficacy and advantages of the recommended reserve assessment method (Rahmann, et al., 2016).

2.3.5 Power system stability amidst integration of WES for reserves

The growing need for flexible dispatch on the generating side is mostly due to the increased use of renewable energy sources. By offering an extra service, other renewable energy sources, like wind power, are also permitted to compete in the markets. In this way, an operating reserve can enable the efficient use of wind energy. A temporal and geographical multi-state model is developed in 2018 research (Lin, et al., 2018) to utilize wind power's potential to provide operating reserve. Reserves are necessary as extra producing capacity to restore the system's balance after unforeseen disruptions, strengthening the electrical system's dependability in the face of unpredictability (Lin, et al., 2018).

However, owing to the possibility of transmission line congestion, reserve deliverability cannot be assured. Although operators struggle to properly allocate reserves among zones while taking into consideration the unpredictability of wind power forecasts, zonal reserve requirements may be a solution to this problem. In a paper that was published in 2020 (Park, et al., 2020), a method for probabilistic zonal reserve needs to accommodate prediction uncertainty for wind power is offered. This method determines the probability distribution of line flows beginning from the system-generating margin and injection shift factor (Park, et al., 2020).

Due to the increased uptake of renewable energy sources, the management of power networks now requires more flexibility. In this way, wind power systems are demonstrating via actual world applications their ability to supply some of the necessary flexibility. Power system designers must thus take into account these new flexible sources to decide how to expand generation capacity. Because wind power units may provide the reserve provision service, (Cañas-Carretón & Carrión, 2020) presented a generation and storage capacity increase plan in 2020. Using a commercial solver, the suggested model is solved as a stochastic linear program.

2.3.6 Available markets for wind energy systems

Wind Power Producers (WPPs) are encouraged to engage in the joint day-ahead energy and reserve market (JERM) by recent changes to the laws controlling the electricity market as well as technology advancements in wind farm control. (Hosseini, et al., 2020) provide an improved bidding process for the WPP's optimal dispatch in the JERM in a study that was published in 2020. The proposed approach employs a unique bi-objective, two-stage chance-constrained stochastic model that completely accounts for a variety of revenue streams from both day-ahead and real-time phases (Hosseini, et al., 2020).

2.3.7 Review discussion on wind energy with Operating energy reserves

Globally, the integration of renewable energy sources into the grid is rapidly gaining traction. Traditional resources like fossil fuel-powered power plants are gradually being replaced by renewable energy sources like solar and wind. As a result, there renewable energy sources have to take over some of the grid services that were provided by traditional generators like operating reserves for example. The primary problem with using renewable energy facilities to provide operating reserves is that their resources are sporadic.

The provision of grid services, such as operating reserves, from wind energy systems in the US, South Africa, and Global countries was examined in this portion of the literature study as listed in the Table 2.2 below.

Table 2.2 Wind energy utilized to support the grid ancillary services

Wind energy is utilized in the US to supply grid services	Wind energy is utilized in South Africa to supply grid services	Wind energy is utilized in Global market to supply grid services
Frequency regulation	Frequency control	Power balancing
Voltage support	Voltage control	Grid stability
Spinning reserve	Reactive power compensation	Reactive power compensation
Non-spinning reserve	Spinning reserve	Grid support
Regulation up/down	Non-spinning reserve	Ancillary services
Contingency reserve	Load following	

The following are some identified research gaps of wind energy systems being used as operating reserves:

- One of the reserve gaps that this research addresses is the use of wind power as a substitute for conventional operating reserves. To dispatch active power from the wind energy system to balance the supply and demand on the grid, an active power control loop was established in Chapter 5 Section 5.4. This study uses a wind energy system to supply a regulating reserve, and it is conducted in a practical manner to gauge its efficacy.
- Examining the possibility of using wind energy to supply additional grid services, like frequency regulation and voltage support — In the case studies simulated in section 5.5 of chapter 5, a 15% increase in load has an impact on both voltage and frequency. By utilizing the active power control algorithm that has been created, the wind energy system model is capable of restoring acceptable levels of voltage and frequency.

2.4 The role of battery energy storage systems

Increasingly, people are turning to renewable energy, mostly for environmental concerns. Incentives are provided with specific goals and decarbonization regulations to promote the widespread adoption of renewable energy sources. 26% of the world's power is expected to come from renewable sources by 2040. Comprehensive long-term plans have also been prepared by a few US states and regions to cut greenhouse gas (GHG) emissions by around 80% below 1990 levels by 2050. Utilizing renewable energy sources is essential to lowering GHG emissions. The increase in renewable energy suppliers has noticeable effects on the electricity system's reliability. Unlike traditional generators, the generation of renewable energy providers is heavily dependent on the weather. Furthermore, there is an increase in both the forecasting uncertainty for grid power output and the unpredictable nature of the power system's generation.

2.4.1 BESS for WES support in operating reserve provision

Utilizing energy storage systems (ESS) to control the erratic and intermittent production of wind farms makes sense. Simple: to compensate for drops in wind power plant output, excess wind energy is stored and released appropriately. However, putting this concept into reality is not simple. Its technological and/or economic feasibility is contested. Although some recent research suggests that ESS may be used to boost the transient stability of wind farms, keep the right voltages at the point of connection, and lessen the unpredictable and intermittent nature of their power generation. In this study's research, a battery-based energy storage device is being considered.

A battery energy storage system (BESS) has lately piqued the interest of academia due to its short reaction time when compared to a diesel engine and gas turbine as a feasible choice for relocating daily peak loads. However, compared to other energy storage systems, BESS has greater initial investment and ongoing maintenance expenses. Furthermore, although voltage control and frequency modulation are crucial for connecting to the electrical grid, adjusting them for BESS is challenging (Kang, et al., 2014). In research that was published in 2014 (Kang, et al., 2014), it is proposed a unique intelligent energy storage service model that utilizes the understanding of distributed energy storage and maintains a constant reserve margin by storing leftover power. From the findings of this study, it can be inferred that the reserve margin will approach the goal value more closely the more energy storages there are (Kang, et al., 2014).

The electrical grid's reliability and security are impacted by the shift to a significant proportion of renewable energy sources. As a result, countries in the EU are considering enabling distributed generators to take part in the provision of auxiliary services. A promising technology that could make this transformation possible is the grid-connected Battery Energy Storage Systems (BESS) (Brivio, et al., 2016). Numerous studies have improved BESS control for the supply of auxiliary services, in addition to research efforts to regulate and integrate BESS into the current power systems.

2.4.2 Published control strategies for BESS participation in operating reserve provision

Brivio et al. published a model in 2016 to examine methods to increase BESS potential for supplying key control reserves. This study article suggests distinct approaches or models. The first model put forth is known as variable-droop, and it allows for time-varying droop regulation in order to ensure PCR availability and avoid state-of-charge saturations. The second approach put out, energy arbitrage, charges and discharges the battery at economically advantageous periods (Brivio, et al., 2016).

The temporary inertial response of a permanent magnet synchronous generator-wind turbine generator was optimized by Wu et al. (2017) using a unique inertial control approach based on torque limit management in a variety of wind speed changing scenarios. Using a small-scale battery energy storage system, a coordinated control strategy between the battery energy storage system and the permanent magnet synchronous generator-wind turbine generator is established in order to address the secondary frequency drop issue that arises during the rotor speed restoration. In order to mitigate the risk of excessive BESS energy consumption, this control technique may gradually remove the involvement of the battery energy storage system after the system frequency returns to the expected level (Wu, et al., 2017).

In order to optimize the financial benefits of a battery energy storage aggregator, (Hu, et al., 2018) suggested an optimization model for the supply of variable ramping goods in day-ahead energy and reserve markets. Following an explanation of the fundamentals of flexible ramping products, comparisons with conventional supplemental services, pricing schemes, and market model extensions that incorporate flexible ramping goods are discussed (Hu, et al., 2018).

Ito et al. (2018) detail the current situation and the steps being done to maintain supply and demand in order to minimize the intermittent nature of renewable energy in a paper that was released in 2018. According to this study, the best option for providing spinning or balancing reserve for power system stability in order to relieve various difficult conditions—such as renewable energy ramp down, sudden loss of generation, etc.—is to use battery energy storage systems due to their short reaction times (Ito, et al., 2018).

Mohy-ud-din et al. (2018) propose a three-stage day-ahead scheduling method for a wind farm with integrated multi-unit battery energy storage systems. 2018 saw its publication. The first phase involves calculating a statistically flexible dispatch margin based on long-term wind prediction error data to address the forecast uncertainty of wind power. This approach's second phase of research provides a potent optimization formulation that increases the amount of money it generates. In order to guarantee equal cycles of charging and discharging without suddenly switching between charging and discharging modes, a multi-unit battery energy storage system scheduling algorithm is ultimately presented in the third stage (Mohy-ud-din, et al., 2018). The battery energy storage system's lifespan will be extended as a result. The suggested approach is presented against scenario-based stochastic optimization and worst-case realization-based robust formulation. The outcomes of the simulation show that the suggested strategy beats previous methods in terms of reducing uncertainty, total revenue, extending the life of battery energy storage devices, and calculation time (Mohy-ud-din, et al., 2018).

Peaking capacity delivery could lead to a significant energy storage market in the United States. Due to laws in many areas and the possibility of achieving life-cycle cost parity with combustion turbines when compared to batteries with longer lifespans, batteries with a four-hour lifespan are especially important. However, whether or not a four-hour energy storage system can offer peak capacity depends largely on the sort of power demand. The maximal capacity of four-hour batteries nationally starts to decline at roughly 28 GW, based on historical grid conditions. The feasibility of utility-scale energy storage acting as peak capacity for the American electrical system is examined in a paper from 2020 (Denholm, et al., 2020). The findings indicate a sizable potential for energy storage to take the role of peaking capacity (Denholm, et al., 2020).

In 2020 (Kwon & Kim, 2020), a plan for utilizing energy storage systems as supplemental service resources, in particular as a spinning reserve, was given. To employ energy storage systems as a spinning reserve resource, the technique used with conventional generators must be improved due to the energy-constrained nature of energy storage systems. The authors of this study offer a method for redefining the energy storage system reserve margin as the difference between the charging and discharging capacities as part of the stochastic optimization of unit commitment. However, this study only considered the viewpoints of system operators, assuming that they had complete control over the scheduling of ESSs in the power system. To create a more workable paradigm, ancillary service markets could be considered with independent operators that own the ESSs and run them to optimize their earnings (Kwon & Kim, 2020).

In a report that was published, (Dratsas, et al., 2021) investigated the effect of energy storage systems on the resource sufficiency of power networks facing increased levels of renewables penetration. For the computation of energy storage capacity value and the evaluation of system capacity sufficient, a coherent strategy utilizing the Monte Carlo technique is presented to achieve this. The main emphasis is on battery energy storage systems, whose capacity values are estimated for different power and energy combinations (Dratsas, et al., 2021).

2.4.3 Review discussion on BESS with Operating energy reserves

According to published literature, battery energy storage systems can provide support to operating reserves in several ways:

- **Frequency Regulation:** BESS can help maintain grid frequency by charging or discharging to balance generation and load.
- **Spinning Reserve:** BESS can provide rapid response to grid events, offering spinning reserve capacity to stabilize the grid.
- **Non-Spinning Reserve:** BESS can offer non-spinning reserve capacity, providing additional power to the grid when needed.
- **Regulation Up/Down:** BESS can absorb or inject power to help maintain grid stability.
- **Contingency Reserve:** BESS can provide backup power in case of unexpected outages or grid events.
- **Ramping Reserve:** BESS can help manage ramp rates during periods of high demand or generation variability.
- **Flexibility Services:** BESS can offer flexibility services, such as load shifting and peak shaving, to support grid operations.
- **Grid Support:** BESS can provide voltage support, reactive power compensation, and grid stability services.

According to the published literature, wind power combined with Battery Energy Storage Systems (BESS) can effectively provide operating reserve provisions. Wind power, although intermittent, can be combined with BESS to provide various operating reserve services, such as:

- **Spinning reserve**: BESS can store excess energy generated by wind power, releasing it quickly to the grid when needed.
- **Non-spinning reserve:** BESS can provide a quick response to grid imbalances, stabilizing the system.
- **Regulation services:** BESS can help balance grid frequency by absorbing or injecting power in response to changes in wind output.

The following is a possible configuration of the wind energy system and the battery energy system:

1. Wind farm generates electricity and feeds it into the grid.
2. BESS is connected to the wind farm and stores excess energy during periods of high wind production.
3. When the grid requires operating reserve capacity, the BESS is dispatched to release stored energy and support the grid.
4. The wind farm and BESS work together to provide a stable and reliable source of power to meet the grid's operating reserve requirements.

The following are some challenges of integrating wind energy systems with BESS for operating reserve provision:

- Integration and coordination between wind farm, BESS, and grid operators
- Ensuring grid stability and reliability with intermittent wind power
- Managing battery health and lifespan
- Economic viability and revenue streams

The table below, Table 2.3, highlights some research gaps with their definitions of operating reserves provision from WES and BESS which were identified during the literature review. The table also provides a summary that explains how these research gaps are addressed in this thesis.

Table 2.3: research gaps in operating reserve provision with WES and BESS

Research gap	Definition	How this thesis address the gap?
Optimal sizing and placement	Determining the ideal size and location of BESS to maximize operating reserve potential.	This research study sizes the BESS in such a way that it can supply 15% of the peak demand. The BESS is placed on the generation side for operating reserve provision.
Real-time monitoring and control	Developing advanced monitoring and control systems for optimal wind-BESS operation.	In section 5.4 of chapter 5 of this thesis, an active power control algorithm was developed for real-time monitoring and control of the WES and BESS.

Ancillary services and market participation	Exploring wind-BESS participation in various ancillary service markets.	Through this literature review chapter, this thesis explores the wind-BESS participation in various ancillary service markets.
System stability and reliability	Ensuring wind-BESS systems maintain grid stability and reliability.	The modelled WES and BESS are integrated into a modified IEEE 9 bus system in section 5.4 of chapter 5 and a steady state analysis is carried out to investigate grid stability and reliability.
Scalability and grid-wide implementation	Investigating the large-scale implementation of wind-BESS operating reserve provision.	This thesis investigates the large-scale implementation of wind-BESS operating reserve provision. The modelled wind energy system in section 5.2 of chapter 5 has a rated power output of 48MW.

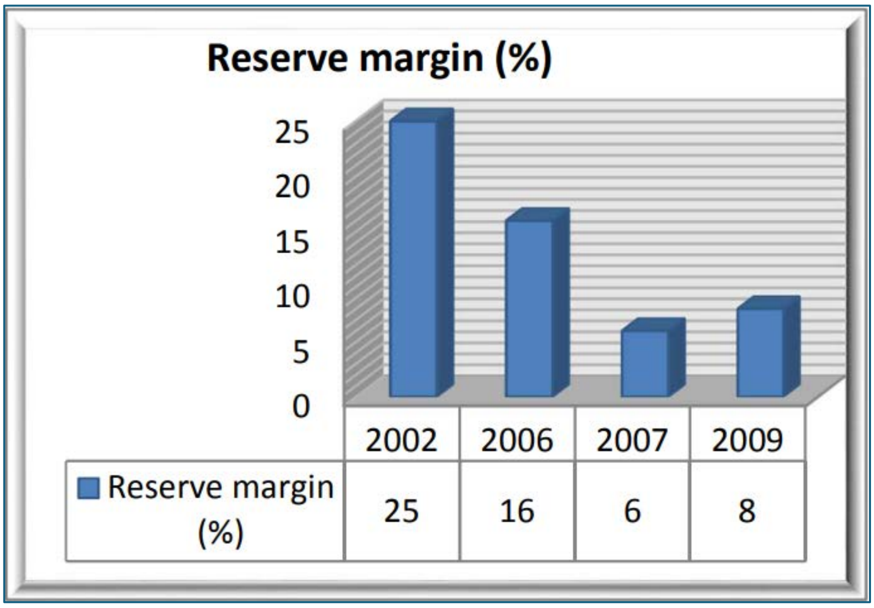
2.5 Electricity reserve margin and storage capacity in South Africa

South Africa is thought to produce and use the most power, according to estimates. Estimates place South Africa's contribution to Africa's electricity production at over half. Furthermore, it has long been believed that the nation has one of the greatest reservoirs of energy. But recently, there has been a slight decrease in the reserve margin. In South Africa, for example, the energy reserve margin dropped from 25% in 2002 to 20% in 2004 and finally to 16% in 2006. Reserve margin was expected to be between 8 and 10% in 2008, which was much below the national goal of at least 15% (Odhiambo, 2009) (Lawrence, 2020).

According to (Amusa, et al., 2009), Between the late 1990s and 2004, investments in new generation and transmission facilities were scaled back, which reduced the gap between supply and demand for electricity and reduced the amount of available capacity. The difference between generation and demand, or South Africa's electrical reserve margin, fell from 25% in 2001 to between 8% and 10% by 2007 (Amusa, et al., 2009) (Lombard & Ferreira, 2014). A power crisis that is emerging as a result of demand surpassing supply threatens South Africa's stated objective of 6% annual economic growth between 2010 and 2014 (Amusa, et al., 2009) (Nkosi & Govender, 2022).

As to Pretorius et al. (2015), there was a notable decline in the electrical reserve both in the run-up to and during the energy crisis, with it falling well short of Eskom's 15% target. Internationally, the typical range for required percent reserves of electricity is 15% to 25%. After load shedding was implemented in 2008, which artificially inflated the reserve, the power reserve curve became distorted. Eskom used power buybacks in 2011 and 2012 to enhance the reserve, which involved paying some energy-intensive consumers to not use energy during those times. Since the end of 2014, load shedding has been used to enhance the reserve, and Eskom has urged major consumers to reduce their electricity consumption by 10% (Pretorius, et al., 2015).

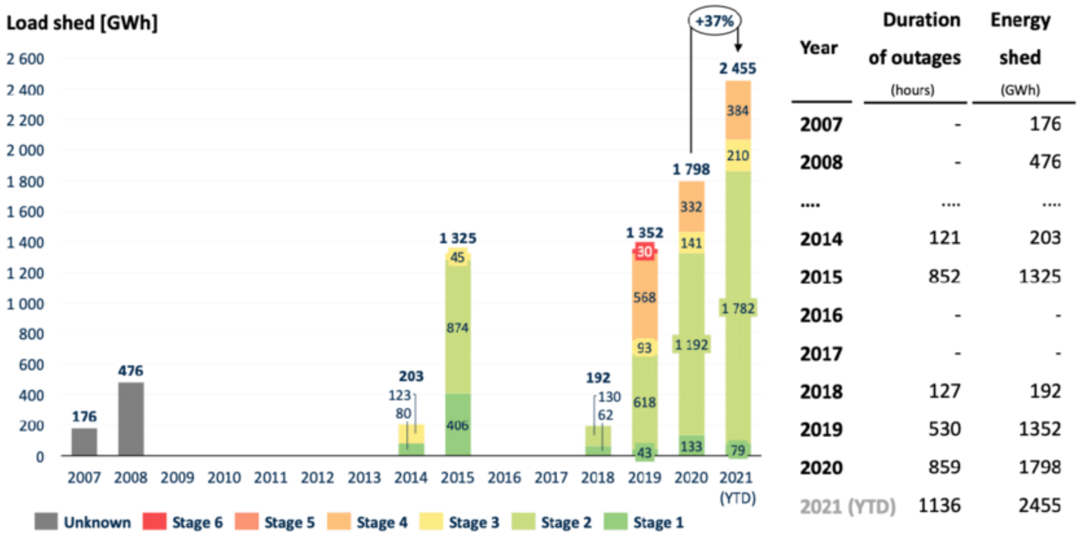
According to the diagram below, Figure 2.4, the reserve margin in South African has been decreasing since the year 2002 (Mwale & Davidson, 2014).



	2002	2006	2007	2009
■ Reserve margin (%)	25	16	6	8

Figure 2.4: **South Africa’s Reserve margin (Mwale & Davidson, 2014)**

The South African national electric utility's aging power plant infrastructure and unscheduled blackouts have been seriously impeding the power producer's capacity for years, and these bottlenecks remain a major barrier to further growth. Figure 2.5 shows how since 2018, there has been an increasing number of load-shedding days, raising worries from utilities about an overloaded electric grid, an outdated, unreliable, and poorly maintained generating fleet, and the need for additional production capacity. They will always be at risk from load shedding until much additional electricity capacity is provided. The commercial case for promoting programs for power efficiency and the production of renewable energy has strengthened due to load shedding and increased levies by municipalities and national power providers (Thango & Bokoro, 2022).



Year	Duration of outages (hours)	Energy shed (GWh)
2007	-	176
2008	-	476
....	....	....
2014	121	203
2015	852	1325
2016	-	-
2017	-	-
2018	127	192
2019	530	1352
2020	859	1798
2021 (YTD)	1136	2455

Figure 2.5: **The number of days of load shedding in South Africa (Thango & Bokoro, 2022)**

This load shedding is in line with the declining Energy Availability Factor (EAF) used by South Africa's power utility to determine how efficiently electricity-generating facilities operate in proportion to the electrical energy they supply to the national grid. According to predictions, the EAF would be about 61.8% in 2021, 65% in 2020, and 66.9% in 2019. The estimated EAF for 2018 was around 71.9%, barely shy of the 74% goal established by the electricity utility. It had greatly diminished since then. A low of about 53.3% on an EAF average for the week in 2021 was recorded. Figure 5's installed generation capacity demonstrates South Africa's interest in or advancement in renewable energy. It is predicted that by 2030, the proposed capacity will produce around 10.5% of South Africa's generating capacity (Thango & Bokoro, 2022).

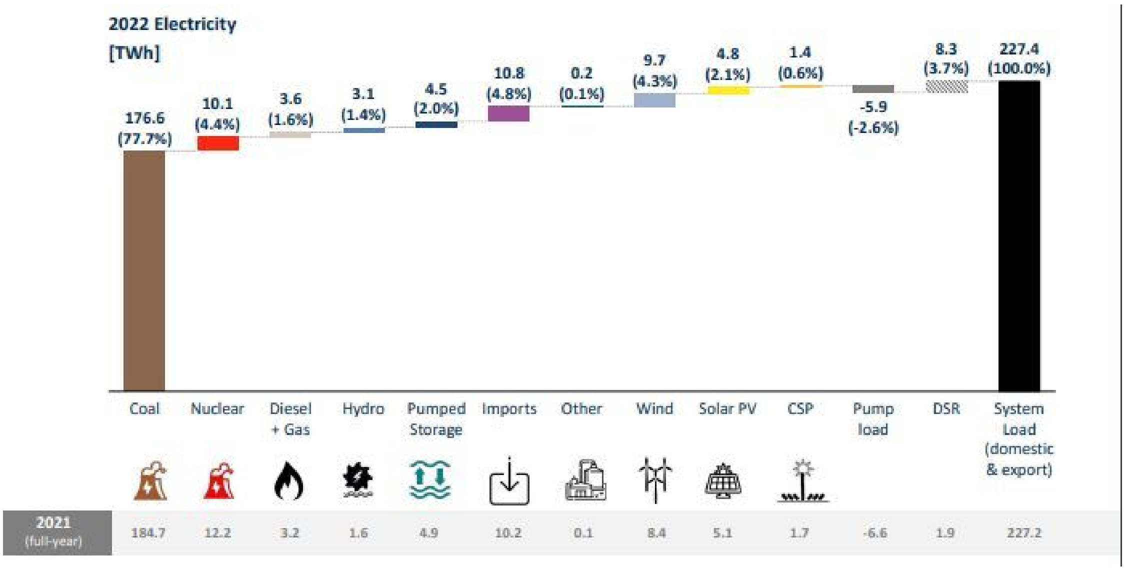
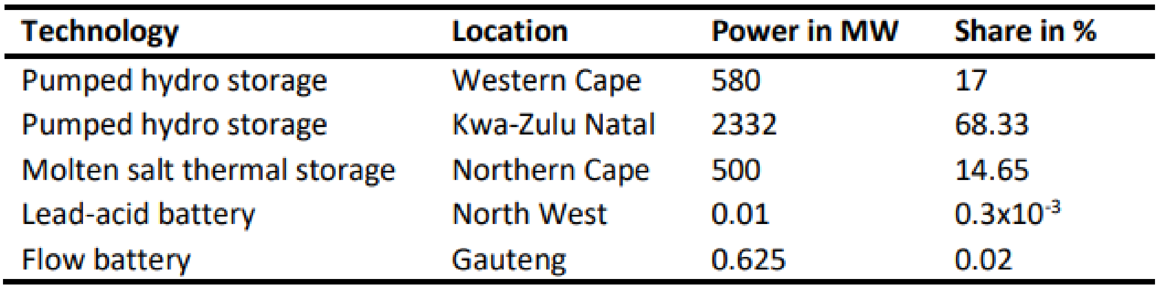


Figure 2.6: Installed generation capacity in South Africa (Thango & Bokoro, 2022)

Cost savings have led to a rise in demand for energy storage systems. Energy time shift, voltage control, frequency control, line upgrade deferrals, and energy smoothing are a few uses for energy storage systems. The greatest financial gains will be realized when the type of energy storage system technology is best fitted with the particular application. Solutions for energy storage systems might be mechanical, chemical, electrochemical, thermal, and thermochemical. In the South African context, ESSs are necessary for applications like grid strengthening and flexibility. The nation's network of pumped hydro storage facilities already supports the grid, but a battery energy storage system is now required. The three most apparent technology options are batteries made of lithium-ion, vanadium redox, and sodium sulphide. For South Africa, the implications of where the BESS should be located and the execution challenges have not yet been considered. The three BESS options listed offer the best performance, are most cost-effective on a large scale, and have the highest potential for commercial success (de Waal & Bekker, 2019).

According to (Seleem, 2017), over 3412 MW of energy storage has been installed in South Africa. The graphic below, Figure 2.7, shows the number of energy storage project deployments, some of which are already operational and others which are still in the planning stages but will start up shortly. The diagram demonstrates that pumped hydro storage projects make up the majority of deployed projects. Only two projects use batteries, and one of those was just announced and is not yet operational. This figure also highlights the dearth of battery deployment projects and suggests that more battery deployments may be necessary to meet SA's renewable energy ambitions.



Technology	Location	Power in MW	Share in %
Pumped hydro storage	Western Cape	580	17
Pumped hydro storage	Kwa-Zulu Natal	2332	68.33
Molten salt thermal storage	Northern Cape	500	14.65
Lead-acid battery	North West	0.01	$0.3x10^{-3}$
Flow battery	Gauteng	0.625	0.02

Figure 2.7: Share of deployed electric storage systems in South Africa; adapted based on (Seleem, 2017)

One of South Africa's largest issues is the energy industry, which requires periodic load shedding to prevent the national system from failing. The largest electricity supplier in South Africa, Eskom, has plans in place for the construction of additional power plants. In the KwaZulu-Natal Province, there are three pumped storage peaking stations: Ingula (1300 MW), which is now under construction, Drakensburg (1000 MW), and Palmiet (400 MW). The use of subsurface pumped hydroelectric energy storage as a bulk energy storage replacement technology in South Africa and as a way to help the country's restricted electrical infrastructure has both financial and environmental benefits (Khan & Davidson, 2017).

(Thango & Bokoro, 2022) examines a few South African situations where energy storage systems have been used with PV producing, highlighting their operational modes, energy storage kinds, and current outcomes. According to the case study provided, Li-ion batteries are suggested as a temporary workable solution to solve the issue of power shedding in South Africa since they are determined to be profitable from both a technical and economic standpoint (Thango & Bokoro, 2022). Several technological problems, including output power smoothing, load shaving, frequency regulation, PV plant dispatch ability, and energy arbitration, can be avoided by using the offered control algorithms and their corresponding duration (Thango & Bokoro, 2022).

2.5.1 Review discussion on reserve margin and storage capacity in SA

South Africa's strategy and roadmap for reserve margin with BESS (Battery Energy Storage Systems) is outlined in various documents and initiatives, including:

- **Integrated Resource Plan (IRP):** Aims to increase electricity generation capacity, including renewables and energy storage.
- Grid Code: Outlines requirements for grid connection and operation, including BESS.

- **Renewable Energy Integration Strategy:** Focuses on integrating renewables, including wind and solar, with energy storage.
- **Energy Storage Framework:** Guides the development and deployment of energy storage technologies, including BESS.
- **National Grid Development Plan:** Includes plans for grid expansion and upgrade, enabling BESS integration.
- **South African Energy Storage Alliance (SAESA):** Industry-led initiative promoting energy storage development and deployment.

The roadmap includes:

- **Short-term (2020-2025):** Develop and deploy BESS projects to address reserve margin concerns.
- **Medium-term (2025-2030):** Integrate BESS with renewable energy sources, enhancing grid stability.
- **Long-term (2030-2040):** Achieve a minimum reserve margin of 2,000 MW, with BESS playing a crucial role.

This plan seeks to lower greenhouse gas emissions, increase the use of renewable energy sources, and maintain a stable and dependable grid. In South Africa, using Battery Energy Storage Systems (BESS) for operating reserves presents several difficulties, including:

- High upfront costs: BESS technology is still relatively expensive, making it challenging for widespread adoption.
- Limited grid infrastructure: South Africa's grid infrastructure may require upgrades to accommodate BESS integration.
- **Energy storage policy and regulation:** Clear policies and regulations for BESS in reserve margin applications are still evolving.
- **Grid stability and reliability:** BESS must ensure grid stability and reliability, which can be complex in South Africa's energy landscape.
- **Renewable energy integration:** BESS must effectively integrate with renewable energy sources, like solar and wind, to ensure a stable grid.
- **Land acquisition and permitting:** Securing land and permits for BESS deployment can be time-consuming and costly.
- **Technology and performance risks:** BESS technology risks include performance, durability, and lifespan concerns.
- **Skills and training:** Adequate skills and training are required for BESS operation, maintenance, and repair.

- **Cybersecurity:** BESS systems require robust cybersecurity measures to prevent unauthorized access and ensure grid stability.
- **Public acceptance and education:** Raising awareness and acceptance of BESS technology among stakeholders and communities is essential.

From the above-mentioned challenges, this thesis aims to address issues such a grid stability and resilience, renewable integration, skills and training, and public acceptance and education.

2.6 Comparison of research on optimum operating reserve margin calculation methods

Table 2.4 provides the summary of review findings on the optimum operating reserve margin methods reported in the available literature

Table 2.4 reviews the summary of the optimum operating reserve margin methods

	Paper	Aim	Methods and Model used	Limitations	Achievements
1.	(Ela, et al., 2010). **Evolution of Operating Reserve Determination in Wind Power Integration Studies**	The primary focus of this research is on approaches for determining operational reserves for power networks with significant wind energy penetration.	This paper reviews several recent research on wind power integration, with a focus on the All Island Grid Study (Ireland) and Eastern Wind Integration and Transmission Study (US) methods employed to calculate the operational reserve needs.	The majority of wind power integration studies conducted thus far assume an hourly unit commitment and system dispatch while taking security considerations into account	Future research problems and trends related to operating reserve determination are succinctly highlighted in this report.
2.	(Le & Chowdhury, 2010). **Probabilistic planning reserve margin studies at the California ISO**	The goal of this study was to advise on how to create the Planned Reserve Margin (PRM).	The Multi-Area Reliability Simulation program from GEII was the primary instrument used in this study (MARS).	The effects of finite energy sources were evaluated using historical performance data, which may not be an accurate	The study was able to determine the reserves needed to keep CAISO at a specific LOLE.

				representation of the current situation.	
3.	(Diewvilai, et al., 2011). **Reserve margin evaluation for generation system using probabilistic-based method**	This research proposes a probabilistic approach for determining the value of an acceptable reserve margin using a dependability indicator termed Loss of Load Expectation.	This study suggests a probabilistic strategy for determining the appropriate reserve margin. The suggested approach can demonstrate the proper range of reserve margin for future load growth, assisting system planners in making plans for the quantity of reserve margin. With a modified Thailand system, the suggested method is tried.	The nation of Thailand is the focus of this study. Some nations may have a higher Loss of Load Expectation than Thailand and may have a different reserve margin at peak load.	The suggested approach would make it possible for system planners to more effectively design generation systems by providing a guideline for the right amount of reserve margin. The percentage reserve margin increases together with the amount of the generic capacity.
4.	(Holttinen, et al., 2012). **Methodologies to Determine Operating Reserves Due to Increased Wind Power**	The approaches utilized in contemporary wind integration analyses and operational practice are presented in this	There is a distinction between deterministic and probabilistic analytical methodologies. Deterministic methods are straightforward, but they run the	It might be challenging to compare the results of different approaches. The	The framework for presenting reserves and the usage of dynamic techniques show how the amount

		study, along with key comparisons between various methods or data.	risk of overestimating the system's costs and reserve needs. Probabilistic approaches, which are more complex and usually computationally costly, are required to define an imposed reliability criterion and the related reserve amount.	outcomes of a dynamic, shifting reserve need cannot be illustrated straightforwardly.	of reserve required depends on both the timing and the required response time.
5.	(Rejc & Čepin, 2014). **Estimating the additional operating reserve in power systems with installed renewable energy sources**	This paper presents an improved probabilistic method for estimating the additional operational reserve in power networks with installed renewable energy sources.	This improved probabilistic method analyzes the dependability of power systems while taking into account the fluctuating generation of renewable energy sources as well as the age of the producing units. The reliability study findings are used as a starting point to compute the additional operational reserve for the power system, which is then added to system operation using	The method depends on several data sets. Yet, gathering the data for the calculations might be challenging. Estimating common cause failures is notoriously difficult.	According to case study findings, the dependability of the power system may be significantly influenced if renewable energy sources produce a sizable share of its total output.

			the established reliability standards.		
6.	(Zafir, et al., 2016). **Relationship between loss of load expectation and reserve margin for optimal generation planning**	This study's main goal is to identify the crucial variables that affect the Loss of Load Expectation (LOLE) level in Peninsular Malaysia.	The LOLE is computed using the WASP-IV Simulation Tool under various scenarios in this study, which includes sensitivity tests on parameters such as peak load and forced outage rate that have an impact on LOLE.	Investment in new generation capacity must be ongoing to accommodate expected load growth and maintain a healthy Reserve Margin.	According to the study, the forced outage (FOR) rate and peak load have a considerable impact on the LOLE level. Because of this, regular maintenance may help to lower the FOR and hence lower the LOLE level of existing generation units.
7.	(Muzhikyan, et al., 2017). **An a priori analytical method for the determination of**	The load following, ramping, and regulating operational reserve needs, as well as their a	The approach is validated using several extensive simulations that model how the power system would function in various	This approach might not work since the grid settings and input data dynamics could	When the reserve needs are established using this

	operating reserve requirements	priori estimates, are all included in this study.	scenarios. This method is used to study the sensitivity of each reserve requirement type to the net load and power system parameters.	change from one period to the next.	way, the system remains in balance.
8.	(Bapin, et al., 2018). **Estimation of Operating Reserve Capacity in Interconnected Systems with Variable Renewable Energy Using Probabilistic Approach**	To assess operational reserve capacity in linked power networks, the research proposes a probabilistic methodology.	A probabilistic strategy is suggested. The method takes into account the possibility of losing generation as well as forecasting errors for load and wind.	Only Matlab was used as a simulation tool. The method was not tried with other software packages.	The reserve schedules' overall costs are the lowest for the linked structure.
9.	(Chongphipatmongkol & Audomvongseree, 2018). **Determination of Reserve Margin based on Specified Loss of Load Expectation**	The strategy for systematically linking the reserve margin and dependability level is suggested in this research.	Until the anticipated LOLE reaches the desired level, this suggested approach fixes the generating data while modifying the demand data, energy demand, and peak load. The reserve margin is then determined.	For other nations, the connection between reliability and reserve margin could be different.	Using this technique, a system planner can change the reserve margin to achieve the required level of reliability.

10.	(Hu, et al., 2018). **Provision of flexible ramping product by battery energy storage in day-ahead energy and reserve markets**	This study recommends an optimization strategy for a battery energy storage aggregator to offer variable ramping items in day-ahead energy and reserve markets to optimize its financial gains.	The proposed model incorporates over-offering risk and BES deterioration compensation in addition to energy, regulatory, and FRP profitability.	This study does not go into great detail about how BESS might be sized to offer operating reserves, nor does it emphasize the advantages BESS's involvement in this market has for the power system.	Studies of certain circumstances have demonstrated that an aggregator may be able to generate more revenue by strategically dividing its resources among diverse goods than by only delivering energy and reserves.
11.	(Qamber & Al-Hamad, 2019). **Power System Market Planning: Capacity Margin Probabilities Calculation**	The primary goal of this research is to calculate the expected loss of load.	By fusing the generating and load models, the developed Capacity Margin Probabilities Calculation model will assess the system by calculating the likelihood of the capacity margin.	This paper bases its case studies on assumptions and not real-life scenarios. The results may be different when using a real power network.	Finding the Capacity Margin for any combined power system generation that satisfied the required peak demand was made

					easier thanks to the study. At 0.0060604, the first negative margin was attained. This value is used to calculate the LOLE and LOLP, the latter of which is 1.21208%.
12.	(Dvorkin, et al., 2019). **Setting Reserve Requirements to Approximate the Efficiency of the Stochastic Dispatch**	The purpose of this study is to identify a less expensive method for calculating reserve requirements.	The approach utilized in this paper is based on a stochastic bilevel program that implicitly improves the intertemporal coordination of the reserve and energy markets while yet remaining compatible with the European market structure.	The authors' consideration of a streamlined market setting with a purely convex representation constitutes a drawback of this technique.	The numerical analyses offered demonstrate the benefits of correctly implementing reserve requirements.
13.	(Talaat, et al., 2020). **Operating reserve investigation for the integration of wave,**	This study examines the viability of combining a variety of renewable energy sources, taking into account the	The three sources, wind, wave and solar energies, can be combined with a microcontroller that also can calculate the operational reserve for each	In this study, the reserve margin is determined only just for a residential building, there is no	This study examines a topic that has not received much research: the operational reserves

	solar, and wind energies	operational reserve created by the blending process.	source separately. The Buck-Boost converter technology is the foundation of this controller.	guarantee that the results will be the same when the same method is implemented on a bigger scale.	of three integrated renewable energy sources.
14.	(Tsujii & Oyama, 2020). **A Study on the Reserve Margin and 10-Minute Spinning Reserve for Wide-Area Supply and Demand Control**	This study's objective is to statistically analyze the SR10 margin while balancing regional supply and demand.	The authors, Tsujii and Oyama, examine the viability of wide supply and demand control by predicting the SR10 margin for each period (month and time of day) and different reserve capacity targets (reserve margin and SR10).	This study uses a Solar PV plant instead of a Wind Energy system.	The results show that wide-area supply and demand control is feasible in terms of supply and demand equilibrium and show how modifying adjacent reserve capacity enables them to maintain the SR10 buffer.

2.7 Comparison of existing papers on wind energy systems with a reserve margin

Table 2.5 provides the summary of review findings on the wind energy system with a reserve margin reported in the available literature.

Table 2.5 reviews the summary of the wind energy system with a reserve margin

	Paper	Aim	Methods and Model used	Limitations	Achievements
1.	(Lin, et al., 2018). **A Multi-State Model for Exploiting the Reserve Capability of Wind Power**	To leverage wind power's potential to supply operating reserves, a temporal and geographical multi-state model was developed in this study.	The first step is to create a multi-state model for multiple wind farms based on correlations between different periods and wind farms as well as the expected distribution of wind power. Second, a quantitative examination of the upward and downward reserve capacity of wind power is carried out utilizing the proposed multi-state model as a basis.	In this study, the erratic character of the wind is not taken into account.	Case studies demonstrate that the proposed MS model is sufficiently resilient to be used in a range of systems.

2.	(Oshnoei, et al., 2018). **On the Contribution of Wind Farms in Automatic Generation Control: Review and New Control Approach.**	This study does a good job of discussing the role of wind farms in the supplemental/load frequency regulation of autonomous generation control.	The performance of the fractional order proportional-integral-differential controller is compared with that of the conventional proportional-integral-differential controller to demonstrate the efficacy of the suggested control strategy in the frequency regulation of a two-area power system.	There is still work to be done in this area of research.	The suggested controller is effective at controlling load frequency for wind farms.
3.	(Karbouj & Rather, 2019). **Voltage Control Ancillary Service From** **Wind Power Plan.**	This study examines the Type-4 wind turbine-based WPP's reactive power capability while keeping in mind practical limitations.	An inventive and successful centralized capability-based control technique that goes above and beyond grid code requirements. It is also suggested to use an adaptive technique to distribute reactive electricity produced by wind turbine generators (WTGs) in a WPP.	The recommended methodologies are tested in this paper using just one simulation package.	The suggested approach has performed better at both supplying and consuming reactive power.
4.	(Rebello, et al., 2019). **Performance Analysis**	This study's main goal is to generate a	This paper presents experimental results of a	Despite being simple, the technique has	A wind farm that participates in the

	of a 10 MW Wind Farm in Providing Secondary Frequency Regulation: Experimental Aspects.	profitability analysis of wind farms that provide secondary frequency control using data from testing.	secondary frequency regulation test carried out on a 10 MW wind farm with Type-V wind turbines. This is a 5 h test of the wind farm's ability to follow an external, historical automatic generation control signal. 1 MW of power is offered on the regulation market with up-regulation provided via a fixed curtailment value. The performance of the farm is evaluated using the performance score method developed by the Pennsylvania–New Jersey– Maryland (PJM) system operator	several drawbacks. One such restriction comes up as a result of calculating the available wind power using the 10-minute average wind speed. As a result, the device occasionally operates badly when the wind speed decreases.	secondary regulatory market might make extra money when the market is favorable, according to experimental data reported in this article.
5.	(Sedighizadeh, et al., 2019). **Optimal energy and reserve scheduling for power systems considering frequency dynamics,**	The goal of this study is to ensure frequency dynamic security by accounting for demand response programs and rapid response energy	The Frequency Dynamics-constrained Unit Commitment problem, commonly known as FDUCB, is described as a Mixed-Integer Linear Programming problem where	The recommended model for wind-generating uncertainty (Case Studies 2 and 4)	By examining the case studies under consideration, it can be seen that employing ESS units to schedule

	energy storage systems, and wind turbines	storage system injections following a generating outage.	energy storage technologies, demand response, and wind turbine uncertainty are taken into account.	requires more computation time.	generation and reserves minimizes the cost of operating the system, prevents wind curtailments, and ensures frequency security.
6.	(Hu & Ryan, 2019). **Stochastic vs. deterministic scheduling of a combined natural gas and power system with uncertain wind energy**	To lower total costs associated with satisfying gas and electricity demand while adhering to operational and equilibrium constraints, this research looks at techniques for addressing uncertainty in the joint scheduling of a combined power and gas system.	Both stochastic programming models and deterministic models with reserves have been created to examine the hourly unit commitment and economic dispatch in the electrical system as well as the hourly working schedule of the natural gas system.	This research formulates the issue using a centralized direct current (DC) power flow model and a static natural gas system, leaving out several sophisticated dynamic power and natural gas limits to make it more manageable.	Results from the simulation reveal that the SP model generates a substantially lower standard deviation and mean cost, demonstrating that probabilistic-scenario-based scheduling of the combined system is better able to maintain a stable cost.

7.	(Cañas-Carretón & Carrión, 2020). **Generation Capacity Expansion Considering Reserve Provision by Wind Power Units**	Because wind power units can utilize the reserve provision service, this study offers a formula for increasing generating and storage capacity.	Using a commercial solver, a stochastic linear program is used to solve the suggested model. To determine the effects of considering wind power reserves while making capacity investment decisions, a case study was presented.	There are no strategies for increasing generating capacity that take into account wind power units' involvement in reserve markets.	When storage costs are considered, the proposed model, in particular, reduces the overall predicted cost by 0.17%, even though investments in wind generating capacity rise by 11%.
8.	(Ai, et al., 2020). **Robust operation strategy enabling a combined wind/battery power plant for providing**	By utilizing the strategies outlined in this paper, a wind/battery power station can compete in	This paper concentrates on day-ahead energy/regulation offering strategy and real-time operation of a wind/battery-based power plant. First, a robust offering strategy for	The example research does not address total revenue since the energy price, reserve price, and monitoring	The results in monetary terms demonstrated how successful the method was. The flexibility,

	energy and frequency ancillary services.	the markets for energy and related services.	energy/regulation reserve based on two historical-data analysis methods is proposed. Second, in real-time operation, an MPC-based real-time operation strategy considering the BESS's energy constraints is proposed to improve the performance of the plant in both markets and to examine the robustness of the proposed offering strategy.	mistake penalty rely on the particular local market conditions of each country.	dependability, and capacity to maintain a symmetrical reserve of power of the wind farm are all improved with the inclusion of a battery energy storage system.
9.	(Rebello, et al., 2020). **Ancillary services from wind turbines: automatic generation control (AGC) from a single Type 4 turbine.**	Examine the potential for auxiliary services to be offered by commercially available wind turbines and provide empirical support.	The income from providing secondary frequency control is computed using estimated performance ratings, yearly site wind statistics, and PJM market pricing data from 2017.	This research is restricted to evaluating how well current wind turbines can deliver the following supplementary service: an additional frequency control.	This study was able to show that the annual revenue from regulation as a whole is more than the revenue from energy alone.
10.	(Björk, et al., 2022). **Dynamic Virtual**	Fast frequency reserves (FFR) will be required	This study addresses a decentralized model matching	The authors' strategy has some drawbacks,	It has been derived how to create a DVPP

	Power Plant Design for Fast Frequency Reserves: Coordinating Hydro and Wind.	by future low-inertia power grids to maintain frequency stability.	problem that involves coordinating traditional (slow) frequency containment reserves with fast-frequency reserves.	such as the design's disregard for ramp rate and saturation limits.	and distribute supplementary FCR services among a heterogeneous ensemble of controlled plants.
11.	(Matthies, et al., 2022). **Provision of Power Plant Equal Ancillary Services by Wind Turbines: From Maximum to Grid-demanded Power Point Tracking.**	The transfer of wind turbines that offer the same ancillary services as a power plant from the existing wind-dependent grid feed-in to an advanced grid-demanded power point tracking control mechanism is the main topic of this study.	The MPPT operation mode of traditional wind turbines was initially touted as the most promising alternative to power plants. The updated grid-stabilizing GPPT control method was created and evaluated based on this. An actual wind turbine test bench was made up for the practical validation.	The method presented in this paper has only been tested on a bench, it has not been tested on real turbines on-site.	This control method might be adequate to eliminate the need for power plants, which have long been seen as indispensable.

2.8 Remarks and observations/discussion

In the past, studies on operating energy reserves have been conducted. Others concentrated on the economic advantages associated with operating reserve margin as well as the algorithms, models, or techniques that can be used to anticipate the optimum reserve margin. Several studies focused on how achieving an optimal operational reserve margin influences power quality. These were some findings from the literature review:

Maintaining a specified level of operating reserve capacity in power systems is essential to preventing power shortages brought on by irregular generator failures, load fluctuations, etc. Having no operating reserves means that when a sudden generator failure or load variation happens, power utilities will be forced to implement load shedding to avoid the possibility of the collapse of the grid. When a power utility implements load-shedding, there are severe consequences for the economy. Building new generating plants to create operating reserves may be expensive but the cost that would be incurred if the grid was to collapse would be a lot more. Electric power system restructuring, or deregulation is slowly being introduced around the world to try and foster competition among generators. According to the reviewed literature, deregulation leads to lower energy prices, getting rid of waste, and raise customer happiness.

The approaches that may be used to calculate or forecast the ideal operational reserve margin while taking into account the growing usage of wind energy systems to generate electricity are the main topic of the first section of this literature review. The influence of wind energy on reserves may be determined using several different approaches. The deterministic and probabilistic approaches are the ones that have been utilized the most in literature. The most prevalent trend seen is the use of dynamic techniques, which take into account particular system situations to reduce overscheduling of reserves.

Both probabilistic and deterministic dynamic techniques are possible; however, deterministic systems may contain a probabilistic component due to their partial reliance on statistical variations in the load and wind. Some approaches use more sophisticated probabilistic techniques, like calculating dynamic LOLP values, to find a reserve amount that maintains risk. The stochastic events occurring in the system, such as producing unit failure and variations in consumer demand, are not taken into account when measuring operational reserves. The primary flaw in deterministic.

Since variable generators are replacing traditional generators, it has been looked into to see whether they can provide any more services. These services include primary and secondary frequency response, reactive power support, operating reserves, ramping reserves, damping, and many others. Even after large-scale wind energy has been incorporated into the grid, the stochastic and intermittent character of renewable power remains a barrier to how renewable electricity might help provide reserves. Wind-based regulatory reserves are subject to murky, conflicting, and evolving rules in US ISO/RTO markets. Wind power plants can create regulatory reserves because they have the speed and duration needed.

South Africa is currently going through an electricity crisis. The installed generation capacity in South Africa is around 54GW but the available capacity is usually half that amount or even less. The operating reserves are almost non-existent. Over 3412 MW of energy storage has been installed in South Africa, with the most dominating technology being pumped hydro storage, followed by Molten salt thermal storage and a bit of battery energy storage systems. However, the South African government together with the South African power utility, ESKOM, has invested in several battery energy storage systems. Most of these battery energy storage systems will be using lithium-ion batteries and most will be supporting renewable energy plants like wind and solar.

2.9 Conclusion

An overview of the literature on themes like operating reserve margin and using wind energy systems to provide operating reserves was provided in the chapter. It explained how power utilities can estimate or compute the ideal operating reserve margin and the idea of operating electricity reserves. The advantages of maintaining an ideal operational reserve margin in terms of price and power quality were also emphasized. This chapter also covers the literature on the usage of auxiliary services provided by wind energy installations. The capacity of South Africa's electrical reserve margin and storage was also examined.

Theoretical aspects of operating reserves (section 3.2), wind energy systems (section 3.3), and battery energy storage systems (section 3.4) are discussed in the following chapter.

CHAPTER THREE

THEORETICAL FRAMEWORK FOR OPERATING RESERVE MARGIN

3.1 Introduction

There are two main uncertainties for an electric power utility that serves loads. Actual load, which is mostly affected by weather, could end up being much higher than anticipated. For instance, significant air conditioning use on exceptionally hot summer days increases load. On the other hand, forced or unplanned outages of a utility's generation units might limit the amount of electricity available overall. Scheduling producing units to provide the demand at the lowest possible operational cost is a crucial part of running a power system. Scheduled units must provide reserve margins to handle load fluctuations or cover equipment failure in addition to the generation needed to satisfy the load. Since each unit can only hold a certain amount of reserve depending on its ramping capacity, such reserve margins must be distributed over several units to ensure reliability. Operating reserves are kept for a variety of purposes, such as everyday operations and the preparation for unanticipated situations. Managing variability throughout the scheduling phase and any lingering forecast inaccuracies during real-time operation are both considered normal operations.

Large-scale wind power plants are a relatively new way of generating electricity, but they are expanding so quickly that power grid managers are struggling to maintain a secure and reliable electricity supply to customers because of the increasing fluctuation and uncertainty of the wind resource. In an effort to outline, understand, and quantify these effects, numerous organizations have carried out wind power integration studies. Researchers and power system operators are currently interested in how wind affects the need for reserves.

The combination of a wind energy system and a battery energy storage system is depicted in Figure 3.1 below, which illustrates the structural diagram supporting the operating reserve theory in this chapter. The power going to the grid comes from both the WES and the BESS, as shown in Figure 3.1 below, and the BESS can only be charged by the WES (Choi, et al., 2018).

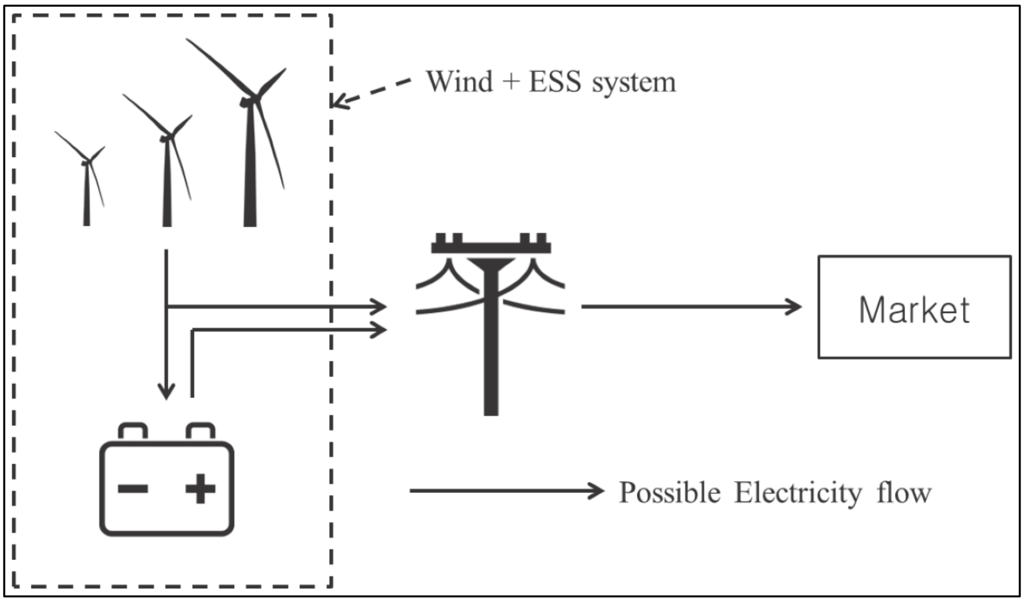


Figure 3.1: Structure diagram Wind+BESS to support operating reserve (Choi, et al., 2018).

The format of this chapter is as follows. The theoretical underpinnings of operating reserve margin are covered in Section 3.2, along with an explanation of the various kinds of operating reserves. The theory of wind energy systems, a recently developed renewable resource with explosive growth, is covered in Section 3.3. The idea behind battery energy storage devices, a technology that could help with reserve provision and resolve the problem of renewable resource intermittency, is explained in Section 3.4. Finally, the idea underlying electricity deregulation, which attempts to bring competition to the electrical market, is explained in Section 3.5 of this chapter.

3.2 Operating Reserve Overview

It is difficult to accurately forecast future demand because the amount of power drawn by loads and the amount of power produced by generators can vary dramatically across a range of timeframes, and important power system components are susceptible to unplanned failure at any time. Power grid managers have a responsibility to acquire varying quantities and categories of operating reserves to deal with forecast errors and successfully service load while preserving system frequency.

Operating reserves fall into three basic categories: non-spinning, spinning, and regulating reserves. Reserves can be injected under both regular and abnormal circumstances, with the primary goal being to acquire a capacity that will be utilized to guarantee that the supply does not exceed the demand. The reserve ancillary services may be provided using a variety of resources, which has increased the utilization of distributed energy resources. The reserves work in such a way that when there is an increase in load, the reserve capacity must be supplied to ensure that there is a balance between the energy generated and the demand. When the generation is not enough to meet the need, they must act quickly (Tshinavhe, et al., 2023).

Operating reserves are used to rectify mismatches between consumer demand and system-generated electricity to keep supply and demand balanced. Operating reserves are subject to numerous definitions and regulations.

Normal-Conditions (Non-event): Both quick random fluctuations and consistent periodic variations are common, yet neither one ever causes the system to lose its secure state. The term "regulation" refers to generating capability that is swift enough to counter a change in load from a most recent prediction which can be in the past 5 to 15 minutes by sending out power usually within. The first kind of fluctuation is handled by this kind of reserve (Mohandes, et al., 2019).

To keep the grid's frequency constant, regulation is required. The majority of the time, quick and modest internet units give regulation. Their controllers' automatic generation control (AGC) design ensures that these units can react swiftly to changes in demand. In comparison to the regulated reserve, the difference between the dispatch schedule and the forecast for five to fifteen minutes in advance necessitates a higher generation capacity as well as a longer response time. The second kind of variation are handled by this "Load following" reserve (Mohandes, et al., 2019).

Abnormal Conditions (Event): Rare, abrupt shifts in the power balance pose a hazard to the grid's security. Despite the rarity of these occurrences, they can significantly harm the system's economy. For instance, in the United Kingdom, they accounted for 50% of all ancillary service costs in the years 2013–2014. Containing these events necessitates the presence of operating reserves which are capable of responding within a short period and can supply large amounts of power for a long time. These needs cannot be met by a single type of equipment. According to response time, spinning and non-spinning reserves are divided into groups. Spinning reserve is further divided into primary and secondary reserve, whilst non-spinning reserve is further separated into tertiary reserve and sluggish reserve (Mohandes, et al., 2019).

The relationship between the various Operating Reserve kinds is shown in Figure 2.2's tree of chapter 2, with the higher-level categories incorporating the lower-level categories. The strictest definition of Operating Reserves is any category of generating capacity used to assist active power balancing. Event reserve and non-event reserve are then separated from this. Non-events are ongoing happenings that happen so frequently that it is impossible to separate them from one another from events, which are serious and infrequent occurrences.

The table below, Table 3.1, further defines operating reserves as they are described in the remaining sections of the thesis and how they are used (Ela, et al., 2010). In this thesis, only the regulating reserve will be investigated practically. The developed active power control algorithm operates automatically which means it cannot be used to practically investigate reserves that require manual operating. The contingency reserves and the ramping reserves are classified as abnormal even reserves and they cannot be practically investigated in this study as all the case studies simulated in this research will not include any abnormal grid events. Regulating reserves are investigated practically in this study as they require automatic operating and have a main aim of balancing the supply and demand which is also the main aim of the developed active power control algorithm. The regulating reserve is adopted and validated using simulation in Chapter 5, section 5.5.

Table 3.1: Operating reserves as they are described in the remaining sections of this thesis and how they are used (Ela, et al., 2010)

Name	Definition	Common terms
Operating Reserve	Utilised for any moment there is a load and generation imbalance. This is a subset of every print reserve category.	Operating reserve (US), reserve, balancing reserve.
Spinning Reserve	This reserve type applies to any category where the resources are immediately responsive and frequency responsive. This service must have been provided by committed generators.	Spinning reserve, synchronous reserve, on-line reserve, responsive reserve
Non-Spinning Reserve	The resources don't have to react to frequency automatically or start responding right away, unlike spinning reserves. There is no requirement for a commitment from the generators offering this service. Simply upward.	Non-spinning reserve, non-synchronous reserve, off-line reserve, quick start reserve
Contingency reserve	When a sudden failure occurs, such as when a generator fails, this is used. Print formats like frequency responsive, non-	Contingency reserve (US), operating reserve (Ireland),

	spinning, and additional prints could be included in contingency reserves. solely upward	primary and secondary reserve (Europe)
Regulating Reserve	used for frequency management and preserving area control inaccuracy under normal conditions. needs autonomous generation control. Both upward and downward.	Regulating reserve, frequency control
Load following Reserve	used for preserving area control error and frequency control during typical (non-event) settings. due to movements that are not random. slower motion than the law requires. no automatic generation control is necessary. downward and upward.	Load following, dispatch
Frequency Responsive Reserve	reserves that deliver the first autonomous reaction to a significant disturbance. downward and upward.	Governor response, primary control (Europe), FRR
Ramping Reserves	used when something fails or when something happens slowly over a lengthy period (like wind ramps or forecast errors). downward and upward.	Variable generation event reserve, forecast error reserve
Supplemental Reserve	Faster reserve is replaced with slower reserve to ensure system security and to restore the level of pre-event reserve. Only upward.	Replacement reserve, supplemental reserve, tertiary reserve (Europe), contingency reserve (Ireland), substitute reserve

3.2.1 Regulating reserves

Regulating Reserves' goal is to maintain the balance in the face of unpredictable disruptions. They respond faster than the electric market does and with shorter turnaround times (Ren, et al., 2017). The imbalance in current is corrected by the regulating reserves (Banshwar, et al., 2017). The shortest scheduling period might be as little as five minutes in certain places and up to an hour in others. The regulating reserve must be used to make up any difference if the system operator sent units believing the net load was going in a specific direction or was a specific size before the next economic dispatch cycle is complete. If the extremely short-term wind estimates are inaccurate, this can lead to a rise in the amount of regulating reserves needed (Ela, et al., 2011).

According to (Ibanez, et al., 2014), As shown in (3.1), the geometric sum of the base need (1% of demand) and the contribution of wind and PV (which account for 95% of errors in 10-minute forecasts) yields the regulatory reserve requirements. Persistence is a factor in wind prediction mistakes, while cloudiness persistence is a factor in PV forecast errors. The latter method removes the forecasts' consideration of the daily solar power cycles. Based on under- and over-forecast mistakes, respectively, calculations are made upward and downward individually. Additionally, this approach imposed a five-minute reaction time requirement on all contributing units.

$$Regulating\ Reserve = \sqrt{(0.01Load)^2 + \phi 95^2_{10min-Wind} + \phi 95^2_{10min-PV}} \qquad (3.1)$$

where ϕ denotes the confidence interval that, in this case, encompasses 95% of the forecast errors for wind and solar power for the next 10 minutes.

According to (3.2), the flexibility reserve is determined as the geometric average of the forecast errors for the hour before for the load, the wind, and the PV (covering 70% of the mistakes). Separate movements are made for moving up and moving down. The ramp rate for the flexibility reserve is not necessary with this strategy.

$$Flexibility\ Reserve = \sqrt{\phi 70^2_{1hour-Load} + \phi 70^2_{1hour-Wind} + \phi 70^2_{1hour-PV}} \qquad (3.2)$$

These reserves are used to balance network frequency and voltage fluctuations because of the dispersed nature of wind and solar producers and variations in their output. An extremely abrupt departure may lead to system failure, equipment damage, or tripped power-producing units (Lund, et al., 2015). The usage of energy storage can decrease these effects. Because continuous operation is needed to respond to oscillations within seconds to minutes, storage systems with a quick reaction time, a high-power ramping rate, and a high cycle capability are a very good choice for providing this service. Since more than 80% of power line interruptions last under a second, a large storage capacity is not necessary in this situation. Various energy storage technologies can be employed to for ensuring system reliability and stability, these technologies include batteries, supercapacitors, flywheels, and superconducting magnets (Lund, et al., 2015).

Published literature indicates that certain power electronics control techniques need to be implemented in order for wind power plants to be able to take part in the supply of power quality and regulation services. The procedure of regulating wind turbines' active power is not simple. It lessens the requirement for, or size of, an energy storage system, which is known to be expensive (Lund, et al., 2015).

3.2.2 Following reserves

Load Following Reserves Maintain equilibrium and frequency in the face of regular, predictable disturbances, primarily in demand. They possess a longer response time than regulatory reserves. The regulating Reserve and the following reserve are extremely similar; however, the following reserve happens more gradually. It is required to account for the fluctuation and uncertainty that occur under typical circumstances. Variability and uncertainty necessitating Following Reserve consequences are more significant than Regulating Reserve, but considerably less random (Ren, et al., 2017).

A comparison between regulating and the following reserve is carried out in Table 3.2 below (Banshwar , et al., 2017). The regulating reserve is controlled automatically whereas the following reserve needs to be operated manually. The regulating reserve reacts in a short period whereas the following reserve reacts in a longer period.

Table 3.2: Comparison between regulating and following reserves (Banshwar, et al., 2017)

Type of Reserve	Pattern	Control	Ramp rate	Reaction time
Regulating	Unrelated and random	AGC control	5-10 x load following	Shorter period
Following	Strong Correlation	Manual control	gradual	Longer period

This form of reserve can be produced through the use of energy storage, which functions by storing energy while demand is low and returning it to the grid when there is a shortage. For this application, energy storage technologies such as hydrogen, batteries, flow batteries, compressed air energy storage, and pumped hydro energy storage are all suitable (Lund, et al., 2015).

3.2.3 Contingency reserves

Most systems now have a contingency reserve that is set aside for scenarios involving a sudden loss of supply. The famous N-1 criteria, the most severe single contingency, must be covered by the system operators or balancing authorities' contingency reserve. Rules specify the quantity of the form of reserve necessary in each balancing area in large, interconnected systems. Particularly, the contingency reserve's automatic, frequency-responsive component can be distributed throughout areas. Reserve conventions have adopted a wider range of strategies for interruptions that occur during routine operations (non-events) (Holttinen, et al., 2012).

Figure 3.2 shows how a response system is supposed to take over after a major loss of a generating unit or plant has occurred (Ela, et al., 2011). Depending on whether there is a loss of supply or load, the inertia of synchronous rotating machines will either contribute to or absorb the energy difference in the immediate aftermath of the occurrence. Generator governors detect the frequency shift after this initial response and start adjusting the input to raise or lower the required energy. Based on the frequency excursion, the governors adjust their output by providing more or less energy.

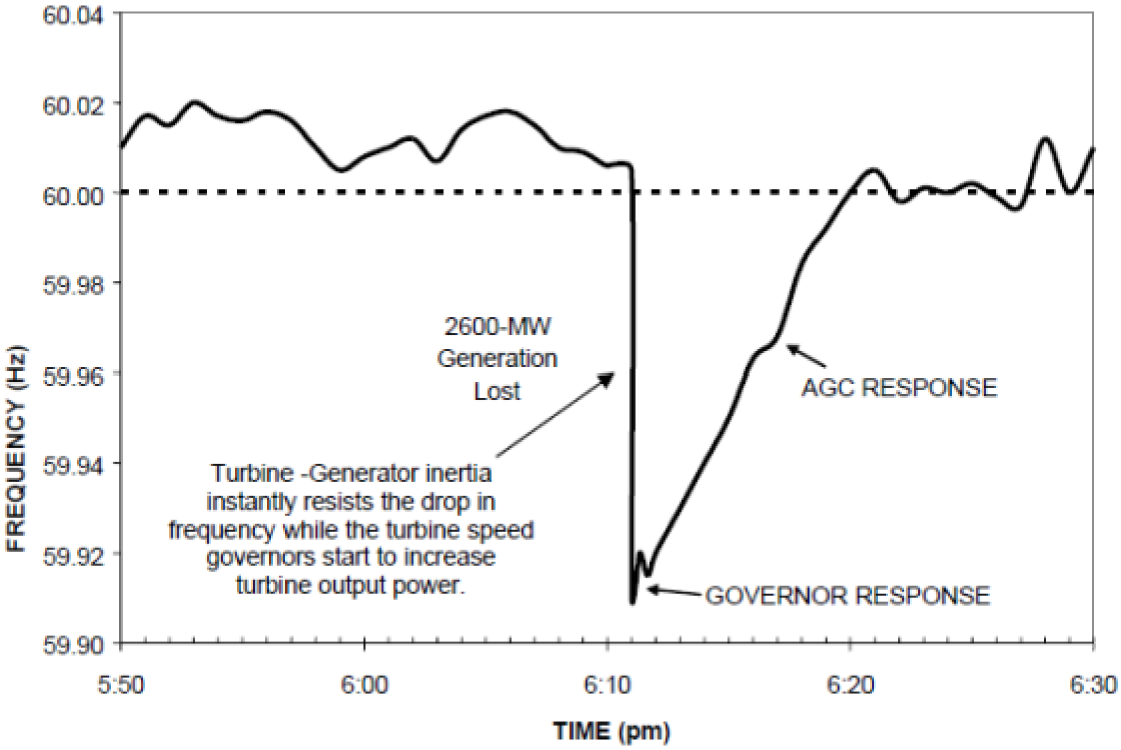


Figure 3.2: **An example of a contingency (loss of supply) occurrence is shown in this diagram, along with common reactions (Ela, et al., 2011)**

3.2.4 Ramping reserves

Ramping Reserves are responsible for responding to long-duration errors or events, such as, for instance, wind ramps or wind forecasting errors, among others. Infrequent large-magnitude events that call for operating reserves may occur as a result of the increasing unpredictability of wind and solar. The specific balance area determines how Ramping Reserves and Following Reserves are divided. For instance, following reserves might account for 95% of potential deviations, whereas ramping reserves might take care of the final 5% (Ren, et al., 2017).

3.2.5 Primary reserves

Primary reserve is a subset of contingency reserve. Therefore, this reserve forms a portion of the contingency reserve that must respond automatically to an increase or decrease in frequency. The response time for this kind of reservation is between 0 and 30 seconds. Because spinning machines slow down to provide inertial energy during loss of supply contingency events (instead of speeding up during loss of load events), the frequency will decrease (Ren, et al., 2017).

Primary reserve is necessary to keep frequency variances from getting out of hand. Keeping an optimum primary reserve ensures that generators are protected from events that can cause damage due to big frequency variations. This reserve can also set off under-frequency and over-frequency relays that might disconnect generators reduce system load, or both to avoid damage to equipment (Ela, et al., 2011).

The primary control reserves can be calculated as follows (ENTSO-E):

$$P_{pri.}^{country} = \frac{E_{prod}^{country}}{\Delta f_{max.ss} \cdot \Sigma_{ENTSO-E} \cdot E_{prod}^{country}} \cdot \Delta P_{cont.} \tag{3.3}$$

3.2.6 Secondary reserves

This continual reserve is automatically activated. For as long as there is still a deviation in the network that needs to be corrected, this type of reserve will remain in operation. The reaction times for this reserve range from 30 seconds to 15 minutes (Ren, et al., 2017). This type of control makes an effort to lower the area control error and return the frequency to its nominal value (Milligan, et al., 2010).

According to ENTSO-E, the secondary reserves can be determined using the following formula:

$$P_{sec.}^{country} = \sqrt{a \cdot L_{max} + b^2} - b \tag{3.4}$$

The following empirical formula, which does not differentiate between incremental and decremental reserves, can be used to determine the minimum secondary reserve (UCTE) (Riedel & Weigt, 2007):

$$R = \sqrt{aL_{max} - b^2} - b \tag{3.5}$$

where L_{max} is the highest expected load for the control region (in MW) and R is a guideline for a secondary control reserve. Empirically established values for the parameters, a and b. The values of a and b for UCTE and ENTSO-E are respectively 10 MW and 150 MW (Riedel & Weigt, 2007).

3.2.7 Tertiary reserves

This reserve can be manually engaged and used for up to 15 minutes to respond to large imbalances in the control area and/or significant congestion issues (Ren, et al., 2017). To return primary and secondary control units to the reserve state, tertiary control, which responds more slowly, is activated (Milligan, et al., 2010).

This reserve is noteworthy since it is the only type of reserve whose deployment is caused by a reserve imbalance rather than an energy imbalance. Tertiary reserves don't always need to recover resources as quickly as primary reserves do. By gradually increasing production (or reducing consumption), tertiary reserves can restore the power system's reaction capabilities, enabling the quick resource that was used to balance the system to go back to reserve mode. How quickly the system must be set up for an event that follows the original event in the same direction (such as an energy surplus or shortfall) will determine the actual response time. This reserve type has to retain its reaction up to the point where the reserve it was covering for is ready to take over (Ela, et al., 2011).

By deducting the suggested minimum secondary control from the largest generation capacity in the control region, it is possible to determine the recommended minimum amount of tertiary control. As a result, the system is guarded against the largest generation unit tripping or its network disconnecting (Riedel & Weigt, 2007).

According to UCTE, the tertiary reserves can be calculated as follows:

$$P_{tert.}^{country} = P_{sec.}^{country} - Gen_{Largest} \tag{3.6}$$

The next section, section 3.3, covers the theory related to wind energy systems. In this thesis, the potential of wind energy systems in the provision of operating reserves is being investigated through practical simulation using RSCAD/RTDS. The wind energy system is used in this research to provide the regulating reserves to balance the active power in the grid. The following section classifies different types of wind energy systems, highlights the opportunities and challenges of wind energy system on the grid and also touches on grid reliability and resiliency with wind energy systems.

3.3 Wind energy systems

Due to global population growth, rising per capita energy consumption, and extensive industrialization, there is an unceasing increase in the energy demand. Conventional fossil fuels are not widely available. Consequently, there will be additional energy crises in the future. Because of this, the usage of renewable energy sources, including solar, wind, biogas, ocean, tidal, and others, is expanding rapidly. One of these that offers the most promise is wind energy. For more than a millennium, people have used wind energy for a variety of things all around the world. Wind energy has been utilized throughout history in a variety of ways, including the use of sails on boats and rafts and the powering of mills to grind grains (Chaudhuri, et al., 2022).

Figure 3.3 below shows the process of generating electricity from the wind resource for grid integration (Mahela, et al., 2019). In this research, a type 2 wind turbine is adopted, and this type of a wind turbine uses an induction generator which requires excitation capacitors. The type 2 wind turbine exports AC power to the grid.

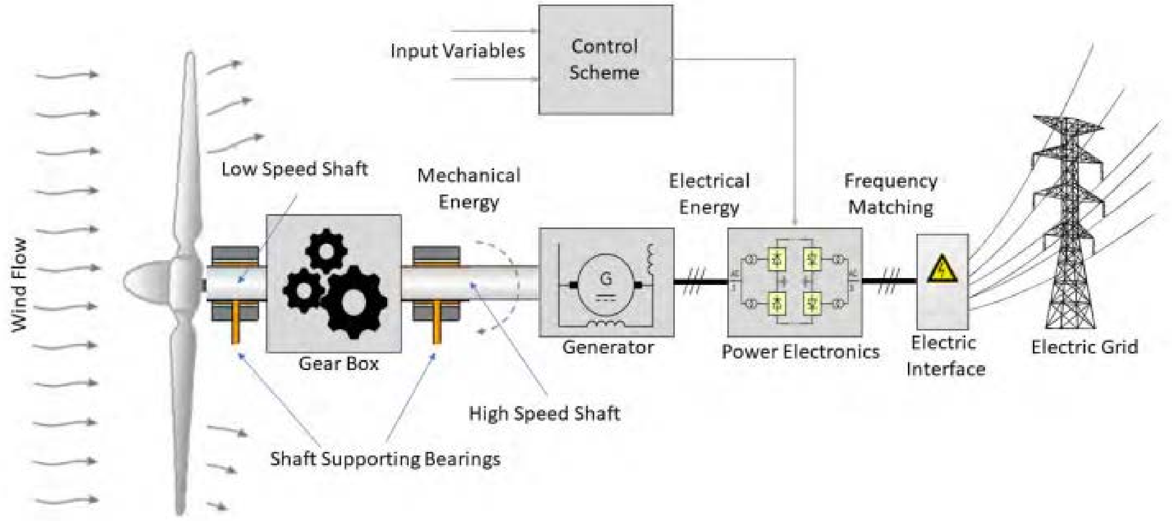


Figure 3.3: **Process of generating electricity from wind for grid integration (Mahela, et al., 2019)**

3.3.1 Classification of WES's

We now use a variety of wind turbine types as shown below in Figure 3.4 (Wagner, 2018). The horizontal axis wind turbine is the most popular gadget. This turbine just contains a few rotor blades that have been modified for aerodynamics; these blades may usually be rotated around their long axes to change the pitch of the turbine. This kind of turbine is quite effective. Since "high-speed engines" are needed to keep the gear transmission and generator small and fairly priced, it is exclusively utilized for the production of energy (Wagner, 2018).

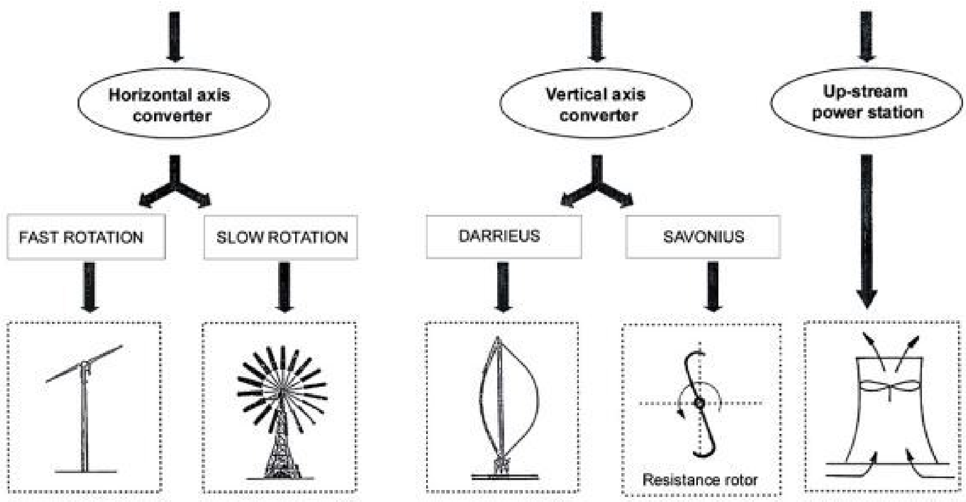


Figure 3.4: A description of the various types of wind turbines (Wagner, 2018)

3.3.1.1 Classification of wind energy systems

The electrical output of turbines is another way to classify them. The size of the wind farm is determined by the output power. Based on this, the three categories of currently used turbine system technologies are as follows:

- **Low power turbines:** According to IEEE Standard 1147-2019, these wind turbines operate from 100 kW to 500 kW (Chaudhuri, et al., 2022).
- **Medium power turbines:** According to IEEE Standard 1526-2019, this category includes turbines with an output ranging from 500 kW to 200 kW (Chaudhuri, et al., 2022).
- **High-power turbines:** According to IEEE Standard 1563-2019, these high-power turbines operate from 2000 kW to 5000 kW. These are systems that carry out extensive electricity production. These are included in the big wind farms connected to the power networks in charge of distributing energy throughout cities (Chaudhuri, et al., 2022).

3.3.1.2 Power control

Since wind turbines are entirely reliant on wind flow to produce power, power control capability plays a significant role in their design. Each turbine has a specific power rating, as was already mentioned. When the turbine is exposed to winds that are more powerful than what they were built to tolerate, this power is exceeded. Even while this results in higher power, there is a risk of mechanical failure because of increased vibrations and the associated imbalanced loads. As a result, when wind speeds increase, power production is constrained. Three controlling techniques—passive stall, active stall, and pitch controllers—can be used to accomplish this. The phase lock loop controller and grid side controller are the additional control strategies (Chaudhuri, et al., 2022).

3.3.1.3 Turbine topologies

For Types 1 through 3 induction generators, a gearbox is required to match the turbine speed to the generator speed (high-speed shaft). Type 4 can be purchased with or without a gearbox, depending on the generator type. Figure 3.5 below depicts the four various forms of WTGs, from Type 1 to Type 4, in order to be the IEEE 1547-2018 standard as published by the IEEE Standards Association (IEEE 1547-2018, 2018) (Muljadi, et al., 2012).

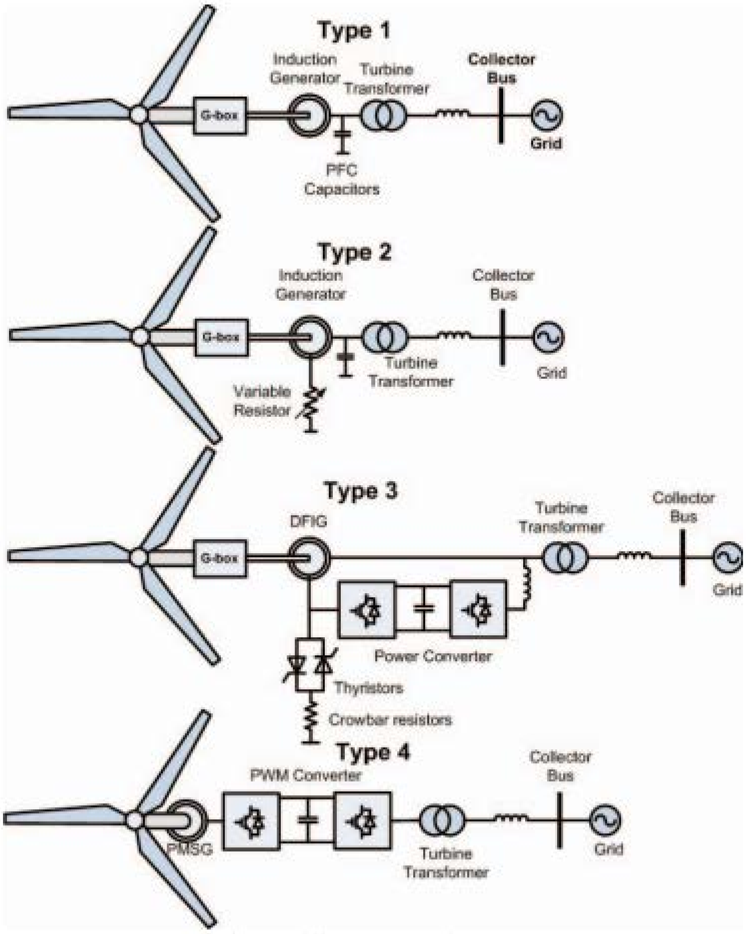


Figure 3.5: Various forms of wind Turbines (Muljadi, et al., 2012) (IEEE 1547-2018, 2018)

3.3.2 Wind Turbine Model

A moving object's ability to maintain its existing condition unaltered is generally referred to as inertia (Wang, et al., 2018). System inertia is the term for a system with rotating masses that resist changes in rotational speed. The spinning mass's inertia constant is calculated as follows to determine the amount of inherent resistance:

$$H = \frac{J\omega_0^2}{2S_N} \tag{3.7}$$

The power generated by a wind turbine can be expressed as (Liu, et al., 2017) (Liu & Liu, 2020),

$$P = \frac{1}{2}\rho \cdot A. C_p.(\lambda, \beta)v^3 \tag{3.8}$$

$$C_p.(\lambda, \beta) = c_1\left(c_2 \cdot \frac{1}{\lambda_i} - c_3\beta - c_4\right)e^{-c_5\left(\frac{1}{\lambda_i}\right)} + c_5\lambda$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \tag{3.9}$$

$$\lambda = \frac{\omega_m \cdot R}{v} \tag{3.10}$$

The mechanical torque of the wind turbine can be calculated as follows (Nasiri, et al., 2015):

$$T_m = J_{eq}\frac{d\omega_m}{dt} + B\omega_m + T_e \tag{3.11}$$

When there are grid faults, the turbine's drive train acts like an untwisted torsional spring, which reduces the amount of electricity produced. This property causes the generator speed to oscillate at a frequency determined by the equation below (Hansen & Michalke, 2007).

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{J_{eq}}} \tag{3.12}$$

3.3.3 Wind energy on the grid

Due to its special characteristics, wind energy presents both new opportunities and challenges for the operation and design of power networks. Ongoing research is being done to determine standards and the best methods for conducting wind integration studies. This subsection highlights some of the challenges that are introduced by wind energy system to the grid including the need for more operating reserves, the challenges of strategic planning and their challenge of output power prediction. This subsection also touches on the effect of wind integration on voltage and frequency.

3.3.3.1 Increase in operating reserves

Due to both the short-term (between 1-6 h) unpredictability of wind energy, which can be large, and its low predictability, system operators have the responsibility to increase the level of operating reserves (Colak, et al., 2015).

3.3.3.2 Effects on strategic planning

Long-term (or strategic) planning for the power system is viewed as being critically dependent on assessments of the generating fleet's ability to consistently fulfil the anticipated load demand over an extended period. One method of evaluating wind energy's contribution to the future power system's dependability is to look at its capacity factor, which can be thought of as the amount of wind energy that will undoubtedly always be available. Since wind is so unpredictable, this is much more difficult to research than non-intermittent conventional generation technologies. As a result, no approach has gained general acceptance, and the most cautious ones assign wind energy a capacity factor of 0 (Colak, et al., 2015).

3.3.3.3 Output power prediction

The parameters of the generation before the integration of wind power into the grid, as well as the unit's production cost and spinning reserves, were of interest to system operators to assist them with the commitment process (Lerner, et al., 2009). The forecast is essential before large wind power plants can be connected to the grid to reduce generating costs because when it is not performed correctly, the need for high operating reserves arises. Unanticipated ramp occurrences can also reduce the grid's dependability. Last but not least, forecasting has been useful for network management when using wind turbines as an electrical source (Giebel & Kariniotakis, 2017). There is no perfect way to forecast the power produced by wind, wind is one of the hardest meteorological variables to do forecast. Each methodology has benefits and drawbacks, making it useful in some situations but inappropriate in others (Lahouar & Ben Hadj Slama, 2017).

The diagram below, Figure 3.6, highlights two methods that can be used to predict the output of wind energy systems. The output of wind energy system can be predicted using a deterministic approach or by an uncertainty analysis (Ahmed, et al., 2020).

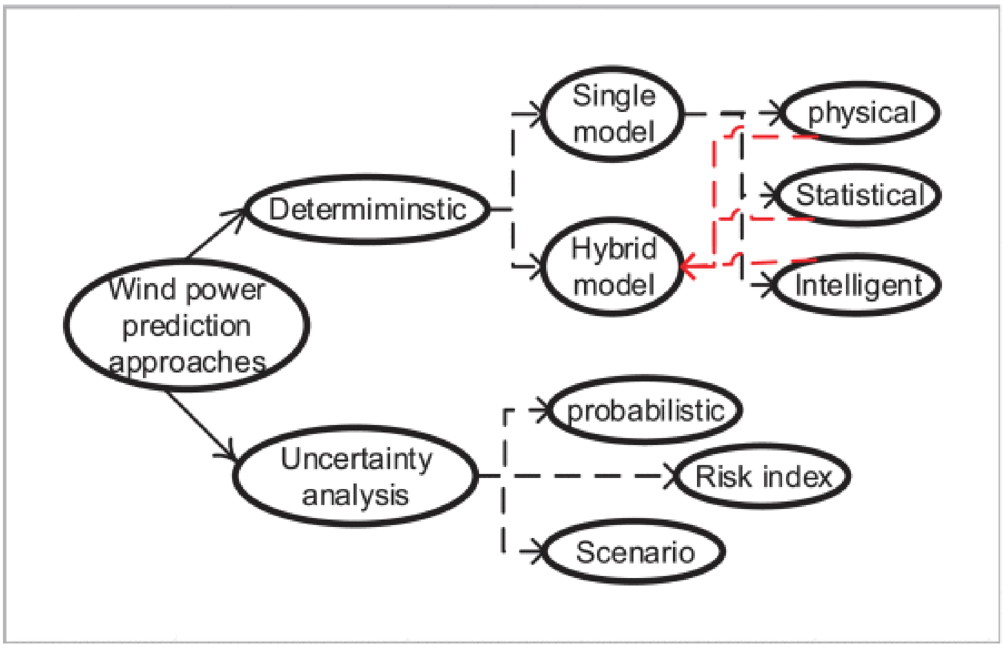


Figure 3.6: Wind prediction approaches (Ahmed, et al., 2020)

3.3.3.4 Voltage support

The majority of wind energy systems use induction generators, which are known to be reactive power consumers by nature, to transform the kinetic energy from the rotating wind turbines into electrical energy. An induction generator needs a specific amount of capacitance across the stator terminals to be excited, and in this situation, that capacitance is provided by the grid's reactive power. As a result, these systems cannot supply reactive power to the grid because they need reactive power to operate (Li, et al., 2018). When the grid is supplying reacting power, the voltage is affected.

3.3.3.5 Frequency

The electrical grid's total inertia is reduced as a result of the addition of wind power, and this effect is particularly significant for smaller, isolated systems (Sang, et al., 2019). The mechanical system is often isolated from the electrical system by most wind power plants' control systems in the event of any disturbance, which lessens the contribution of wind power plants to the network inertia (Ekanayake & Jenkins, 2004).

According to published literature, the use of energy storage systems for frequency regulation has proven to be the best economical way to reduce the likelihood chance of frequency occurrences that coincide with conditions of low wind speed. During periods of low wind speed, energy storage systems can compensate for the amount of active power that is lost due to a reduction in wind power output. Wind farms should serve as the principal source of primary reserve. Furthermore, advancements in wind speed monitoring and forecasting methods might increase the efficiency of regulation algorithms and cut down on wasted wind energy (Attya, et al., 2018).

The subsection above, subsection 3.3.3, highlights some of the challenges that are introduced to the grid by the integration of wind energy systems. These challenges include the potential increase in the operating reserve margin, the challenges of strategic planning, the difficulty in predicting the power output, and their contribution to the need for voltage and frequency support. The following subsection, subsection 3.3.4, highlights the solutions that can be provided by wind energy systems to some of the above-mentioned challenges or to grid reliability and resiliency. This subsection highlights the possibility or the potential of wind energy system contributing to voltage and frequency support and also flexibility dispatch.

3.3.4 Grid reliability and resiliency

There are two methods to sum up the foundational elements of network reliability. Stability in the electrical network can be ensured by balancing the demand and generation. If there is an imbalance, generation or demand must be quickly reduced. This is known as frequency support. Secondly, the voltage at the point of connection to the grid must be maintained within certain limits depending on whether the electrical network is operating under normal or contingency conditions to avoid a situation where the grid collapses. Although these services are an integral part of the traditional generation system, the dynamics of the grid have changed as a result of the arrival of renewable energy sources such as wind turbines (Ahmed, et al., 2020).

3.3.4.1 Voltage support

Voltage and reactive power regulation refers to the capability of an electrical system to supply reactive power according to the necessity to ensure that the voltage stays maintained within certain limits as per the standards depending on whether the electrical network is operating under normal or contingency conditions. Voltage regulation can now be achieved through the use of wind power plants when controlled accordingly by power electronic control circuits. This service can still be provided even in periods when the plant is supplying active power to the grid (Ahmed, et al., 2020).

In order to comply with utility grid requirements, a wind farm must normally be able to run continuously at the rated value at a set power factor (pf) over a predetermined range of frequencies and voltages at the grid connection point (Ullah, et al., 2009).

The following is an expression of the current I_c passing through the converter,

$$I_c = \frac{\sqrt{P^2+Q^2}}{V_g} \tag{3.13}$$

The converter current is maximum when the grid voltage is at its lowest and the wind farm's active and reactive power are at their rated levels. This can be computed as follows,

$$I_{c,max} = \frac{\sqrt{P_R^2+Q_R^2}}{V_{g,min}} = \frac{\sqrt{P_R^2+(P_R \tan\theta_R)^2}}{V_{g,min}} \tag{3.14}$$

where the rated active and reactive power of the WF, respectively, are P_R and Q_R. When P_R is assumed to be the base of the system, the maximum current per unit reduces to:

$$I_{c,max} = \frac{\sqrt{1+\tan^2\theta_R}}{V_{g,min}} \tag{3.15}$$

The following is an expression of the current V_c metered across the converter,

$$(\frac{VcVg}{X})^2 = P^2 + (P\tan\theta + \frac{V_g^2}{X})^2$$

$$\Longrightarrow V_c = \frac{X}{V_{g,max}} \sqrt{P^2 + \left(P\tan\theta + \frac{V_g^2}{X}\right)^2} \tag{3.16}$$

The converter voltage reaches its maximum when the system frequency, grid voltage, and wind farm's active and reactive power are all at their rated values. The maximum converter voltage (line-line rms) that may be achieved per unit:

$$V_{c,max} = \frac{f_{max}X}{V_{g,max}} \sqrt{1 + (\tan\theta_R + \frac{V_{g,max}^2}{f_{max}X})^2} \tag{3.17}$$

The formula below can be used to determine the wind farm's maximum reactive power injection capacity:

$$Q = min\{Q_c + Q_v\} \tag{3.18}$$

$$Q_c = \sqrt{(V_g I_{c.max})^2 - P^2} \tag{3.19}$$

$$Q_v = \sqrt{(\frac{V_{c,max}V_g}{X})^2 - P^2} + \frac{V_g^2}{X} \tag{3.20}$$

3.3.4.2 Frequency support

The frequency of the system decreases at a rate set by its inertia in the event of an emergency, which could be brought on by the failure of a transmission line or a substantial power source. Before the under-frequency relays start detecting the low frequency and isolating the plant, there are two techniques to adjust the frequency and bring it into acceptable ranges. The first phase makes use of a huge inertial torque, a characteristic of large conventional generators. The second method, known as quick frequency response, entails providing ample kinetic energy as well as a significant amount of active electricity to the grid. Currently, wind turbines may provide this capability by installing controllers (Ahmed, et al., 2020).

The control circuit of a generator performs the primary frequency response function by increasing output to make up for loss or reduction in the case of overproduction. An automated response is started when the frequency drops. Wind turbines can also take part in the primary frequency response if the right controls are in place (Muljadi, et al., 2012).

To control frequency, generators react to the feedback signal and change the frequency until it is at its normal operating level. The frequency regulation service is used during both routine operations and the recovery period for emergencies. Wind turbines can offer this service if there is enough capacity available when it is needed (Eto, et al., 2018).

Numerous academics have looked into the typical control techniques that give the inertia response for grid frequency management in the past (Wang, et al., 2018). These techniques enable the kinetic energy to be released from the rotor, adding more power to the grid and raising the frequency. An inertia response loop was added by Ekanayake and Jenkins (Ekanayake & Jenkins, 2004) to the usual DFIG control architecture.

To increase the grid frequency stability and the system inertia response, some researchers devised approaches based on virtual inertia control (Lee, et al., 2016) (Wang, et al., 2015) (Alepuz, et al., 2013) (Arani & El-Saadany, 2013) (Lee, et al., 2016). When the power loss is neglected, the relationship between the turbine kinetic energy and generator kinetic energy can be summarized as follows,

$$KE = \frac{1}{2}J\omega_m^2 = \frac{1}{2p^2} \cdot J\omega_r^2 \tag{3.21}$$

where p represents the number of generator pole pairs, ω_m stands for the rotor's mechanical rotating speed, and ω_r for its electrical angular speed.

The following formula can be used to calculate the change in kinetic energy brought on by the rotor speed adjustment,

$$\Delta KE_{VSWT} = \frac{1}{2p^2} \cdot J[(\omega_{r0} + \Delta\omega)^2 - \omega_{r0}^2]$$

$$= \frac{1}{2p^2} \cdot J_V[(\omega_{s0} + \Delta\omega)^2 - \omega_{s0}^2] \quad (3.22)$$

$$\therefore J_V = \frac{(2\omega_{r0}+\Delta\omega_r)\Delta\omega_r}{(2\omega_{s0}+\Delta\omega_s)\Delta\omega_s} \cdot J \cong \frac{\Delta\omega_r}{\Delta\omega_s} \cdot \frac{\omega_{r0}}{\omega_{s0}} J = k\frac{\omega_{r0}}{\omega_{s0}} J \quad (3.23)$$

where J_V stands for virtual shaft inertia, ω_{s0} is the grid synchronous speed, and the virtual inertia coefficient is specified as $k = (\Delta\omega_r/\Delta\omega_s)$. The virtual turbine inertia can therefore serve as a representation of the frequency change,

$$P_m - P_g = J\frac{\omega_r}{p^2} \cdot \frac{d\omega_r}{dt} = J_V\frac{\omega_s}{p^2} \cdot \frac{d\omega_s}{dt} \quad (3.24)$$

Since they operate over a wider speed range than standard synchronous generators, variable-speed wind turbines can alter the value of k to provide enough equivalent inertia for the system's frequency regulation (Lee, et al., 2016) (Wang, et al., 2015).

3.3.4.3 Flexibility/Dispatch

Flexible resources can adapt to changes that are anticipated or unforeseen since the electric power system is prone to change. A quick start and stop a minimum (down time/uptime), and a minimal stable generating level are all instances of flexibility. Ramping in down and up directions is another (Hsieh & Anderson, 2017). When in production mode and with a quick response, wind turbines that use power electronics for control can assist this service in a downward direction. If the service is configured with pre-curtailments, it may also be transmitted upward. Despite what has been claimed, because the wind is so unpredictable, it is very expensive to provide this service when wind turbines need it (Chen, et al., 2017).

This thesis aims to investigate the potential of wind energy systems to contribute to active power operating reserve provision. While this may be possible, the issue is that wind energy systems rely on the wind resource which is known to be very intermittent and unreliable. This means that there may be times where the grid requires active power, but the wind energy system is unable to provide the required active power due to a low wind speed. The following section, section 3.4, introduces a battery energy storage system which can be used to support the wind energy system in operating reserve provision. The battery energy storage system can be charged during periods of high wind speeds and can be discharged when there is a need for active power during a period of a low wind speed.

The following section, section 3.4, highlights the overview of energy storage systems, explains BESS sizing techniques and explores the need for battery energy storage systems on the generation side of the grid.

3.4 Energy storage systems

Delocalized electricity production and the addition of variable, erratic sources (renewable energy: solar, wind turbines, etc.) make stabilizing the power network more challenging, mostly because of an unbalanced supply-demand situation. Therefore, it is practical to produce the energy, transmit it, transform it, and then store it if necessary. The need for electrical energy storage has increased since that time. However, storing electricity is challenging since it calls for large, expensive equipment (Ibrahim, et al., 2008).

The "star" of the moment in the field of renewable energy for electricity output is wind energy. Nevertheless, because wind turbines' main source of energy is unpredictable, the power they produce over time tends to be unequal. This simply exacerbates the issues that come with integrating a large number of wind turbines into electrical grids, making it more challenging to manage their contribution (regulating voltage and frequency, wind-farm operation, etc.). However, the equilibrium between supply and demand is what ensures the stability of a network. The capacity to control supply will therefore be a factor in raising the rate of wind turbine integration, a problem that electrical energy storage devices should be able to resolve (Ibrahim, et al., 2008).

3.4.1 Overview of energy storage systems

According to the most widely used classification scheme, there are six different types of energy that are held in energy storage systems: mechanical, thermochemical, chemical, electrical, and thermal energy. Other requirements for energy storage devices include function, response time, and energy storage duration.

Figure 3.7, the figure below, shows how various energy storage systems are grouped based on the kind of energy they can store. There are five different types of energy storage technologies: mechanical, electro-mechanical, chemical, thermal, and electrical (Rahman, et al., 2020).

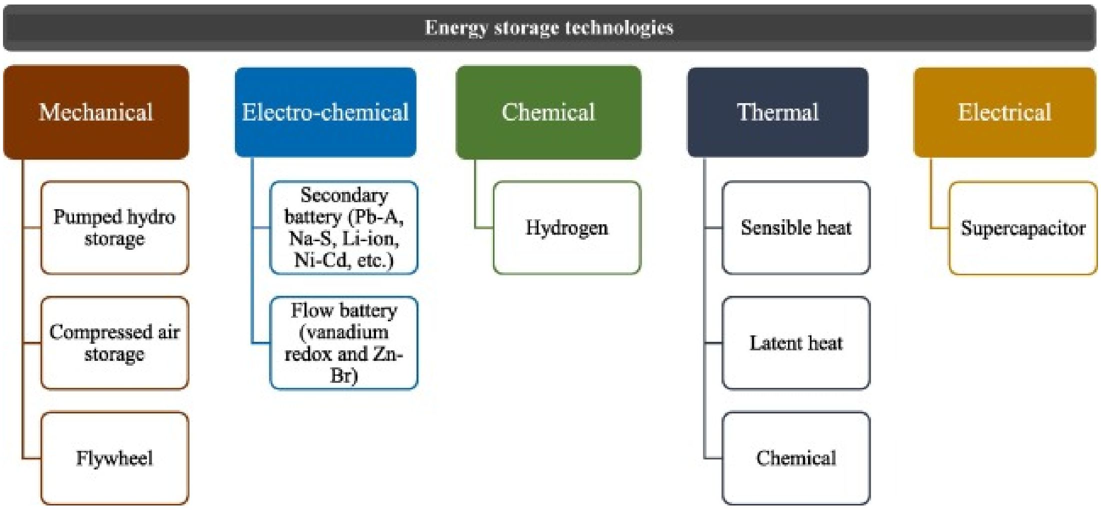


Figure 3.7: **This diagram illustrates how energy storage devices are categorized according to the type of energy they store (Rahman, et al., 2020)**

3.4.2 Different chemical composition for the Battery Energy Storage Systems

Batteries are a very promising supporting system because of their low self-discharge rate, great dependability, and quick response time. When it comes to reducing peak shaving, BESS can be a fantastic substitute for liquid-based generating. It is important to consider the distinct characteristics of each form of storage when considering possible applications. The capacity, energy and power output, charging and discharging rates, efficiency, life cycle, and cost are a few of these factors. Depending on the elements and power of the electronic interface, the various ESS systems exhibit varying confinements (Hannan, et al., 2021).

Of all the energy storage devices, batteries are the most well-established and earliest. In this electrochemical device, electrochemical reactions convert chemical energy to electrical energy. With power outputs ranging from a few Watts to several Mega Watts, they are produced in a variety of sizes and chemistries depending on the application. Depending on how they are used and the type of battery, battery storage is either 60% or 90% efficient (Sufyan, et al., 2019). The following theory talks about a few different battery storage systems.

- **Lead Acid Batteries:** This technology has traditionally been utilized in storage applications. They frequently comprise cells that are immersed in a diluted sulfuric acid solution as an electrolyte because each cell includes a lead dioxide positive electrode and a sponge lead negative electrode. The positive and negative electrodes both change into lead sulphate during the energy release (Olabi, et al., 2021). The primary drawbacks of this battery type are its sensitivity to high temperatures and the need for periodic water maintenance (Sufyan, et al., 2019).

- **Nickel-cadmium battery (Ni–Cd):** This technology has been in use since 1950, which shows how important they are to the sector. Various nickel and cadmium battery types are among them. While the electrolyte is an alkaline solution, the electrodes have a positive and negative charge (Olabi, et al., 2021).
- **Sodium Sulphur batteries:** They contains features made to meet the needs of high-power energy storage applications despite being a relatively new storage technology. This is a result of the storage unit's ability to deliver 50kW of rated power in seven hours (Olabi, et al., 2021). NaS is utilized extensively in wind energy systems and electrical utility distribution grids because it is less expensive and has a higher energy density than conventional battery storage (Sufyan, et al., 2019).
- **Lithium-ion battery:** Most electrochemical battery systems use a cathode, anode, separator, and electrolyte, just like Li-ion cells do. The electrolyte is made up of lithium salt that has been dissolved in an organic solvent, and the anode and cathode are both mostly made of carbon (graphite). The material used to make the separator is a porous polymeric substance (Killer, et al., 2020).
- **Flow Batteries:** Due to their quick response times and energy density of 30 watt-hours per kg or less, polysulfide bromide batteries are excellent for voltage and frequency regulation applications for large-scale grid-level electrical energy. Because it must be pumped, this ow battery's efficiency ranges from 60 to 75 percent. The cost of carbon felt, the challenging sodium polysulfide production process, and cross-contamination after prolonged battery operation are only a few of the issues that still exist with the practical application of polysulfide bromide batteries (Fan, et al., 2020).

A summary of various battery energy storage methods in provided in Table 3.3 below while taking into consideration factors like life cycle, power, and energy density (Hannan, et al., 2021). Table 3.4, on the other hand highlights the advantages and the drawbacks of different battery technologies including lead-acid, lithium-ion, nickel based and sodium-sulphur batteries (de Siqueira & Peng, 2021). This thesis uses the lithium-ion battery technology in the practical work. This technology is still relatively new in the industry and a lot of research is still being done around it. This technology was chosen because of its qualities such as a high life cycle, a high efficiency and a high energy density. This technology is the best technical option for the aim of this thesis, the only issue is that lithium-ion battery are expensive at the moment but the prices are expected to drop over the next coming years.

Table 3.3: Provides a summary of various battery energy storage methods while taking into account factors like life cycle, efficiency, power, and energy density (Hannan, et al., 2021)

Technology	Life cycle	Efficiency(%)	Energy Density(W/L)
Lead Acid	300–3000	70–90	80–90
NiCd	3000	80	50–150
NIMH	2000	66–92	140–300
Li-ion	3000	75–90	250–693
LiCoO2	500–1000	95.7–98.4	2710
LiMn2O4	300–700	80	2310
Flow batteries	2000–20000	65–85	-
NaS	4500	89	10000

Table 3.4: The benefits and drawbacks of the most common battery types are shown in this table (de Siqueira & Peng, 2021)

Battery Type	Advantages	Disadvantages
Lead-acid	High polarization factor, simple installation, and low investment costs.	Poor performance at low and ambient temperatures, short lifetime, and requires frequent maintenance.
Lithium-ion	Long lifespan, high densities of energy and power.	High cost and safety issues
Nickel-based	Longer lifecycle, Low maintenance requirements, and faster discharge cycles.	Low polarization factor, High self-discharge rate, and more expensive than Lead-acid.
Sodium-Sulphur	High energy efficiency, Good power density, high energy capacity, and high life cycle.	Thermal management, seal, and freeze-thaw durability.

3.4.3 Wind-battery energy storage system topology

Because of wind energy's unpredictable fluctuations, it must first be smoothed using battery energy storage before being pumped into the system. Figure 3.8 depicts the fundamental and typical wind-BESS structure for regulating wind power output (de Waal & Bekker, 2019). It is made up of a converter, a battery energy storage system, and a wind turbine. The grid power (Pgrid) is made up of the battery power (PBESS) and the output from the wind turbines (Pwind). The converter joins the battery energy storage system at a point of common connection so that it can deliver or receive power from the system. There are various Wind-Battery Energy Storage System topologies available depending on the requirements of each system.

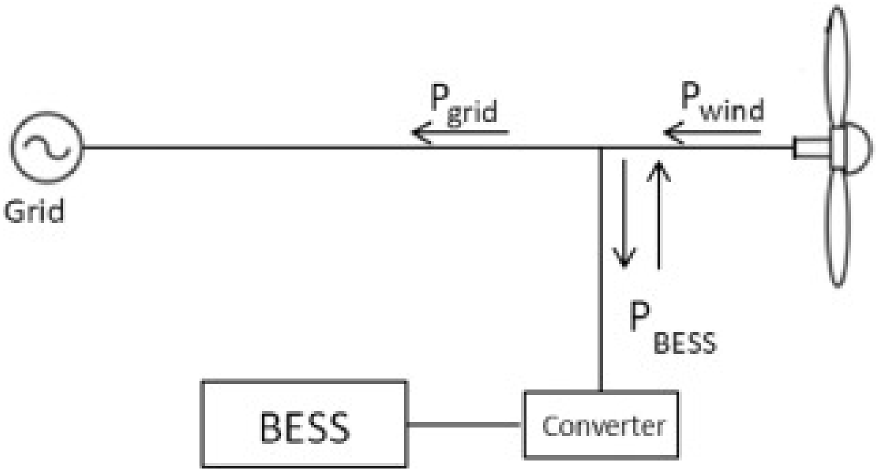


Figure 3.8: **A common topology for a wind-battery energy storage system is shown in this diagram (de Siqueira & Peng, 2021)**

3.4.4 BESS sizing techniques

To get the most economic value out of the storage system, it is important to comprehend the ideal battery size. It might be challenging to choose the right battery size because it affects the battery's efficiency, its longevity, and the price of electricity.

The uncertainty makes this work more challenging when renewable energy sources are used. Both the required load and the cost of energy are directly impacted by this. Both stochastic and probabilistic approaches to BESS sizing have been discussed in the literature. Due to its fluctuating nature, the former is utilized in conjunction with renewable energy sources, whilst the latter is used when storage devices are coupled to the load (Sufyan, et al., 2019).

3.4.4.1 Probabilistic methods

The simplest and prettiest battery sizing methods may be those that use probabilistic methods. The fundamental idea is to maximize the battery size for the chosen criterion by making use of the stochastic character of renewable resources, which are frequently solar or wind. Since they only need a small amount of data from the resources, probabilistic approaches are helpful in circumstances when data availability is constrained. These methods frequently only maximize one or two performance criteria, which prevents them from being applied to complex designs (Yang, et al., 2018).

3.4.4.2 Analytical/deterministic methods

One of the most popular techniques for determining the size of a battery energy storage system is to employ analytical approaches, often known as deterministic techniques. These methods are founded on the analysis of different power system configurations, which also include different system elements that must be optimized in compliance with performance criteria. For instance, when sizing a battery to absorb wind energy, a battery's power and energy capacity can be determined immediately from its daily profile of spilled wind energy.

3.4.5 BESS at the power supply side

Connected energy storage systems can offer grid operators, Distributed Generator plant owners, energy retailers, and customers a variety of services. According to Figure 3.10, which depicts several potential grid applications and classifies them as either power- or energy-intensive, their provision necessitates a high energy reserve or high-power capacity. Their deployment can take anywhere between milliseconds and hours. It can be helpful to learn more about the services themselves before examining how storage has been employed for their distribution (Stecca, et al., 2020).

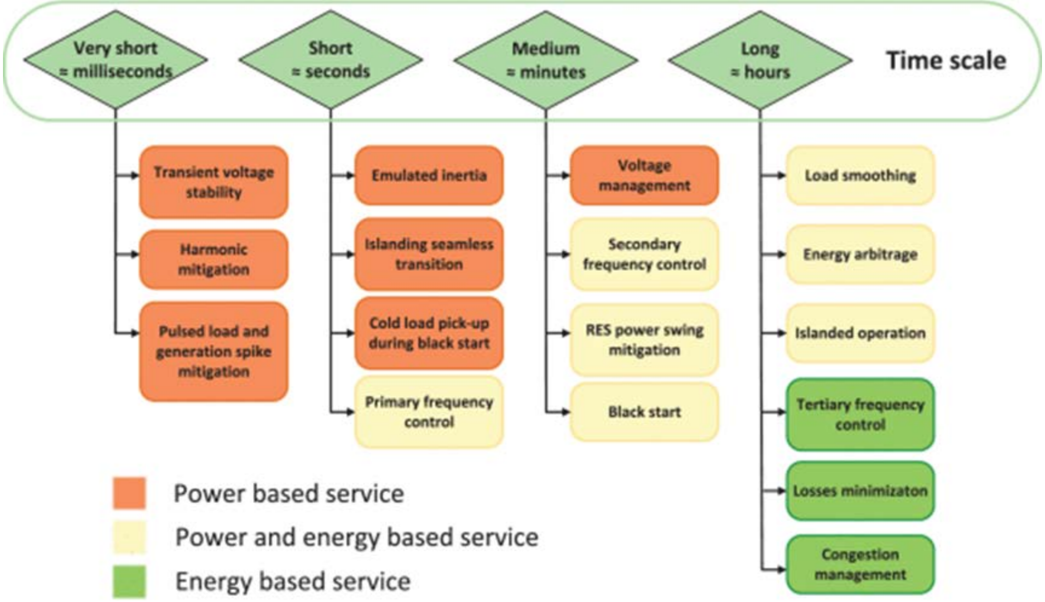


Figure 3.9: Shows the supplementary services that battery energy storage systems can provide (Stecca, et al., 2020)

On the power supply side, battery energy storage devices are most frequently used for the following two purposes. A battery energy storage system can be used with renewable energy sources to control output volatility and track expected output.

Standard thermal power units can also be made more capable of controlling frequency and voltage by combining them with a battery energy storage device.

The BESS can be used on the supply side, power grid size, power distribution side, and power side, as shown in Figure 3.10 below. The BESS can be utilized as a standby power supply, to provide frequency modulation auxiliary services, and to smooth out output fluctuations of sustainable energy sources on the generating or power supply side. (Li & Wang, 2021).

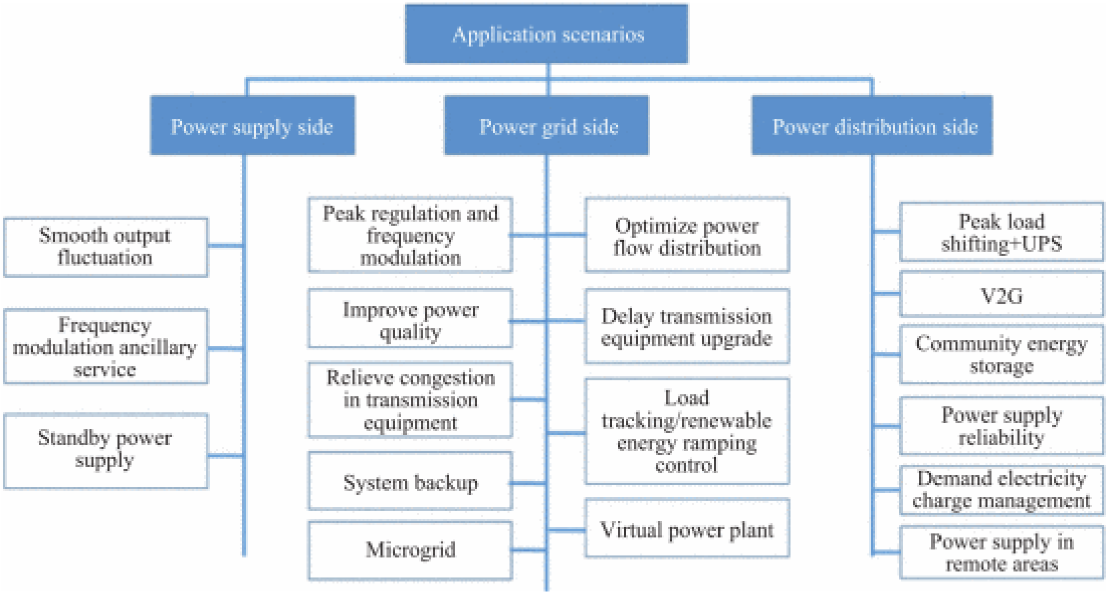


Figure 3.10: **BESS application scenarios (Li & Wang, 2021)**

3.4.5.1 Reducing the fluctuation in power output

New energy sources like wind and photovoltaic energy are characterized by their unpredictable nature and intermittent output. The dispatching and management of the grid will be significantly impacted by the direct integration of new large-capacity energy power-generating equipment, which may result in instability or safety incidents. to meet various technical requirements for the grid connection, the combination of a battery energy storage system and a renewable energy power generation unit can convert the output power's randomly fluctuating output into a suitably steady output (Li & Wang, 2021).

The biggest issue with wind power is how inconsistent the wind is (Wei, et al., 2014). Therefore, battery energy storage devices can be used to reduce power fluctuations. As shown in Figure 3.10, the battery energy storage system can be used to balance out the intermittent output power of the wind turbine.

The BESS capacity's setup must be carefully considered. The impact of consistent output power is not immediately apparent if the BESS configuration's capacity is insufficient. On the other hand, if the BESS arrangement has a very big capacity, the output power is rather stable, but the expenses will rise (Wei, et al., 2014). Therefore, the BESS's capability must be configured suitably.

The following formula is used to calculate the anticipated wind turbine power E for one hour,

$$E = \int_{v_{cut-in}}^{v_{rated}} P(v) \cdot q(v)dv + \int_{v_{rated}}^{v_{cut-out}} q(v)dv \tag{3.25}$$

This is how the capacity of BESS S is determined:

$$S = E \times H \tag{3.26}$$

where H is the period during which a wind turbine maintains a constant output power.

The diagram below, Figure 3.11, shows a typical control board for a wind turbine with a battery energy storage system (Wei, et al., 2014). There is a set power reference, which can be the required active power to balance the generation and supply. When the wind energy system is producing more active power that the power reference, the BESS will be charged using the excess power. When the wind energy system is generating less than the required active power or the power reference, the BESS will discharge and balance the demand and supply.

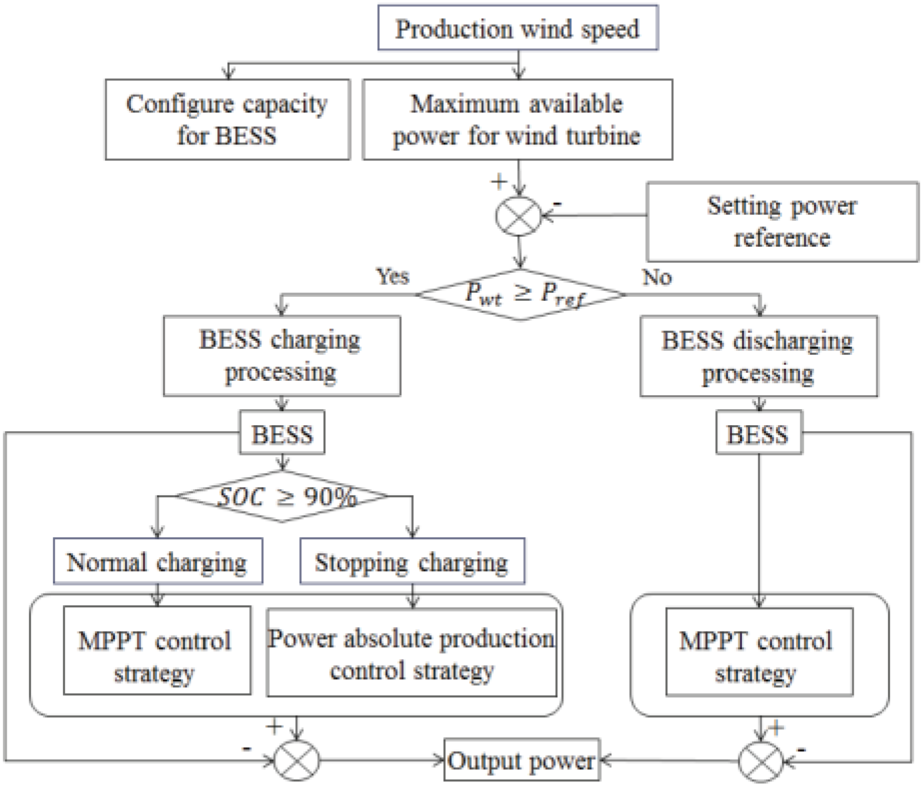


Figure 3.11: Diagram of the control board for a wind turbine with a battery energy storage system (Wei, et al., 2014)

Following are two possible divisions of the battery energy storage system: the charging phase and the discharging phase:

- **Battery Charging**: When the wind turbine's measured power is less than the power reference, the battery stores more energy.

$$P_{wt} - P_{ref} = P_{com} \geq 0 \tag{3.27}$$

- **Battery discharging:** Releasing energy from the battery occurs when the measured power of the wind turbine is less than the reference power.

$$P_{wt} - P_{ref} = P_{com} \leq 0 \tag{3.28}$$

Battery SOC (state of charge) significantly affects how smoothly wind power is controlled. The proportion of capacity Q is known as SOC. How SOC is determined is as follows:

$$SOC = \frac{E_m - \int_0^t U_b \cdot I_b}{E_b} \tag{3.29}$$

where E_m denotes the battery's original capacity, E_b denotes its rated capacity, U_b denotes the battery's voltage, and I_b denotes its current.

The power absolute production control approach uses the pitch angle of the wind turbine to limit output power. The mathematical model of the pitch actuator can be condensed using the first-order structure with a time delay,

$$\beta(t) = \frac{e^{-T_{cd}S}}{\tau_{\beta}S+1}\beta_{ref}(t) \tag{3.30}$$

3.4.5.2 Production monitoring and economic dispatch

The output of modern electric power generation systems is usually erratic and highly challenging to anticipate. The rational and scientific day-ahead, within-the-day, and ultra-short-time (real-time) output plans, which effectively export fresh energy under the premise of adherence to the schedule and storage limits, form the basis of this issue. Today, output monitoring research is conducted in three different ways: day in advance, day in day out, and ultra-short time (Li & Wang, 2021).

Battery energy storage technologies considerably improve both the ability to monitor schedules and the use of new energy power generation. Additional research in this field should focus on the efficient coordination and integration of various time scales in output planning and tracking management techniques, as well as the improvement of the functionality of the BESS's instruction tracking (Li & Wang, 2021).

3.4.5.3 Regulation of frequency using BESS

A utility-scale battery energy storage system's expanding installed capacity offers more doable solutions for updating frequency control tactics and enhancing power system dependability. A BESS can be used to regulate and recover the system's aberrant frequency profile since it serves as an energy buffer. A BESS is widely employed as an AGC unit, system reserve, and for primary frequency control in addition to mimicking inertial response (Li & Wang, 2021).

To calculate the frequency fluctuation in a power system at a certain time instant t, use the following formula (Sanduleac, et al., 2018):

$$\Delta f(t) = f_{ref} - f_{real}(t) \tag{3.31}$$

The battery energy storage system's participation power required to restore the frequency at time instant t is calculated using the formula below (Sanduleac, et al., 2018).

$$\Delta P_{bat}(t) = -\Delta f(t)\frac{P_{max,bat}}{\Delta f_{max}} \tag{3.32}$$

The following formula determines the total amount of energy present in the battery at each time instant t (the simulation time step is 1 second) (Toma, et al., 2016).

$$E_{bat}(t) = E_{bat}(t-1) + \frac{\Delta P_{bat}(t)}{3600} \tag{3.33}$$

The power needed by the primary frequency control, denoted by (36) is increased when the battery state of charge (SoC) falls below a threshold (e.g., 20 to 25%) or rises above a comparable threshold (e.g., 75 to 80%). This additional charging/discharging power is of constant value P_{lt_ch} (lt_ch refers to long-term charging/discharging).

$$\Delta P_{bat}(t) = -\Delta f(t)\frac{P_{max,bat}}{\Delta f_{max}} \pm P_{lt_{ch}} \tag{3.34}$$

In section 3.3 above, the potential of wind energy system participating in operating reserve provision was theoretically explored. To address the intermittency nature of wind energy systems which may lead to the unavailability of operating reserves in crucial moments when they are required by the grid, the battery energy storage technology is theoretically explored in section 3.4 above. The following section, section 3.5, theoretically explores the effect of deregulation on the provision of operating reserves. This means that, in the South African context, the wind energy system and the battery energy storage system providing operating reserves does not need to be owned by Eskom and can be owned by Independent Power Producers (IPPs) to introduce competition. This section highlights factors that led to the deregulation of the electricity market, the impact of deregulation and how operating reserves would be provided in a deregulated electricity market.

3.5 Deregulation

The global power business has adopted a new paradigm based on deregulation and market competition. The responsibility of consistently meeting demand was relatively simple under the regulated system. Utilities are under pressure in the new environment to operate systems with tighter security margins in consideration of lower operating costs as well as taking into account conservative dependability objectives. Operating reserves, which make up a significant portion of auxiliary services under the new restructuring conditions, must be purchased, priced, and properly distributed among generating units (Rashidi-Nejad, et al., 2002).

Deregulation is a change in the laws and ordinances that direct how a system operates. Any sort of market requires technological and economic innovations to improve the standard of the output, boost system effectiveness, and satisfy consumer demands. Consequently, raises both productivity and profit. The electrical market needs to be reorganized as well to increase production. Electricity was considered a service with no market competition before deregulation. In other words, the entire electricity industry was under the authority of a single company. The majority of this organization was government related. The lack of competition eliminated the need for technological advancements. The electricity industry hardly ever included the customer. The customer was compelled to use the service as offered since they had no other option (Raikar & Jagtap, 2018).

The electrical industry underwent restructuring, which significantly altered how it operated. In contrast to the transmission infrastructure, which remained a monopoly, generation and distribution activities have begun to be carried out by independent enterprises that trade capacity in a competitive energy market. These reforms primarily concentrate on system effectiveness and cost reduction by giving utilities options and fostering competition in the market (Banshwar, et al., 2018).

The four main actions that were taken to restructure the electricity market are as follows:

- Monopoly: The period preceding deregulation, distinguished by a lack of competition (Gencer, et al., 2020).
- Wholesale competition: This occurred at the start of the deregulatory process. The purchase of electricity by large consumers can be made either directly from the generators on the spot market or through an electrical broker. Most of these customers are shops and businesses engaged in energy-intensive industries. Then, within already-existing state boundaries, corporatized monopoly utilities were vertically reorganized into three segments: generation, transmission, and distribution/retail supply. By eliminating any unfair advantages that may have lingered in the past, this corporatization process ultimately proved to be a crucial step in levelling the playing field (Lee, et al., 2021).
- Retail competition: In a deregulated market, every consumer has the option to pick where to purchase their electricity (Gencer, et al., 2020).
- Reregulation: Due to internal or external factors, markets may reach a point when things start to go awry, needing regulatory action to support or counteract particular market participant behaviour (Gencer, et al., 2020).

3.5.1 Factors that led to deregulation

3.5.1.1 Technology shift in power generation

Due to their efficiency in producing power over tiny generators, only large generators were chosen in the past. However, as technology advanced and renewable energy sources became available, the use of small generators increased since they could now generate electricity just as efficiently as larger ones (Raikar & Jagtap, 2018).

3.5.1.2 Global trends towards infrastructure industry liberalization

As various theories had predicted, privatization and liberalization did increase economic efficiency. According to a claim, privatization gives access to resources to those who can use them most effectively. According to proponents of this hypothesis, publicly owned electrical utilities won't operate as efficiently as they would if they were privately held (Raikar & Jagtap, 2018).

3.5.1.3 Monopoly utilities’ drawbacks

The several drawbacks of monopolistic utilities encouraged deregulation as discussed below:

- According to conventional rate of return standards, businesses are compensated according to the amount of infrastructure investment they have made. All other things being equal, regulated monopolies prefer to have more assets in the so-called rate base because the rate of return is often fixed. If approved by the authorities, who normally have to approve capital investment in advance, this creates a perverse propensity to overinvest.
- All investment risks are often transferred by regulated monopolies to captive customers, who must bear them during the lengthy useful lives of capital assets.
- Customers that use monopoly utilities, as was previously discussed, have no choice as to the source of supply. They must use the service exactly as it is offered. This is not the case in an open market, where customers have complete choice over who will provide their electricity, for example.
- In certain nations, different monopoly utilities ran operations in distinct regions. The cost of power varied according to location. One consumer was compelled to pay more than another customer who was in a different region. Customers felt discriminated against as a result, yet they were forced to utilize the same supply because they were unable to choose their suppliers (Loi, 2001).

3.5.1.4 Modernization of computerized control and data communication

Control and monitoring of the entire system were one of the main issues with unbundled structures. Monitoring and remote equipment control are less expensive because of the use of advanced data transmission technologies, such as the Internet (Nair & Huang, 2004) (Willis & Philipson, 2018).

3.5.1.5 Benefits of Deregulation

The government switched to a competitive market before deregulation because of the potential benefits of deregulation. Numerous economists have also addressed the many benefits of an open market and industrial privatization. These benefits eventually contributed to deregulation, which had many other causes. The benefits of deregulation were (Loi, 2001):

- A decrease in the cost of electricity.
- The customers would choose who to buy from.
- Customer needs would be prioritized.
- Deregulation encourages creativity and innovation.

3.5.1.6 Deregulation’s beneficial effects on other industries

Other industries had already adopted deregulation before it was applied in the electrical sector. The government decided to implement comparable reforms in the power business because of the success of the reforms in other industries (O'Connor, 1986).

3.5.2 Deregulated Energy Industry

After deregulation, the organization of the power sector varies by country. However, deregulation involved the following procedures or processes in every nation:

- **Unbundling/ Disaggregation:** Disaggregation of integrated structures depending on their primary function was the first step in deregulation. Transmission and Distribution (T & D) in the generation of vertically integrated structures were governed by a single body. However, these operations were divided after deregulation. To perform these tasks individually, distinct sectors were established.
- **Regulations:** The division of the electricity industry into its many operating segments was followed by the creation of regulatory frameworks that outlined the operational confines of each segmented sector and the potential functions of each sector. laws that are unique to each country.
- **Privatization:** In this procedure, the separated industries that were owned by a single monopoly or the government are then sold to private businesses. The market is open to more private players.
- **Competition:** Then, competition is introduced to the sectors. Participants must compete with one another to either sell the power generated or purchase the power for further distribution. Typically, transmission has a natural monopoly while generating and distribution are open to competition.

3.5.3 Impact of Deregulation

Due to changes in capacity, structure, and reforms in the energy industry, the effects of deregulation on various power markets vary. In the majority of countries, deregulation increased the performance of the power sector. The advent of competition and the altered structure of the power market also presented certain difficulties. The following are the most frequent advantages brought forth by deregulatory actions (Raikar & Jagtap, 2018):

- **Reduced electricity cost:** The price of power decreased, which was the main result of deregulation. Increased competition among the generators led to a decrease in the price of electricity. To draw in more clients, the cost was significantly cut. To boost their earnings, the generating stations concentrated more on producing power at lower costs. To produce electricity more effectively and cheaply, more innovative technical approaches were promoted (Rudnick, 1998).
- **Increased electrical coverage:** More consumers flocked to the market as a result of the lower electricity cost. Customers were urged to use the electricity supply more and more. As a result, there were more customers (Rudnick, 1998).
- **Improved productivity:** The production of generating stations also rises as a result of deregulation. The goal of supplying a dependable power supply was the primary driver behind the increasing manufacturing. Due to the lower prices, there is a rise in both customer and energy demand. To fulfill this demand, the utilities began to enhance their capacity. As a result, additional money was invested in brand-new facilities (Rudnick, 1998).
- **Prioritization of customer needs:** Deregulation increased the options available to customers. As a result of the consumers' treatment as customers, their interests are now being considered.
- **Decreased losses:** Deregulatory policies were implemented in many countries, which led to a reduction in both technical and non-technical losses. Technical losses, particularly theft of electricity, significantly decreased. The utilities developed innovative strategies to prevent unauthorized use of electricity (Rudnick, 1998).

3.5.4 Operating reserves in a deregulated market

As part of the reorganization process, there will likely be a sizable unbundling of the products and services provided in the electricity generating, transmission, and distribution sectors. Undoubtedly, the management of electricity given at various times would differ. The topic of auxiliary services is also covered. Depending on the economics of supply and the type of consumer demand, auxiliary services may be divided or combined. Since ancillary services are required for a power system to function safely and securely, they have grown to be a significant challenge. Receiving these services is vital for maintaining the generation-demand balance that is necessary for supply security. Nearly all nations regard frequency control, load following, operating reserves, voltage regulation, black-start services, etc. to be the primary auxiliary services (Banshwar, et al., 2017).

Typically, traditional power plants like thermal and hydroelectric facilities handle the provision of energy and related services. Due to their ability to react quickly, renewable power producers, such as wind farms and photovoltaic power plants, can now compete in the markets for both energy and auxiliary services to increase their profitability (Banshwar, et al., 2017).

3.6 Conclusion

This chapter focused on a theoretical underpinning or overview of operational reserves. The chapter goes on to discuss the classification of wind energy systems, how wind energy affects the power system, the difficulties of integrating wind energy, and how wind energy systems affect grid dependability and resiliency. The idea of energy storage systems is also explained in this chapter, with batteries serving as the primary example. The philosophy underlying the deregulation of the electrical market is also explored in this chapter.

The theory explained in this chapter will be used as a foundation for the simulation work presented in Chapter 4. Next Chapter describes RTDS model and provide simulation results to the research problems related to wind energy systems with operating reserve margins in a deregulated electricity market.

CHAPTER FOUR

MODELLING AND SIMULATION OF THE MODIFIED IEEE 9 BUS SYSTEM ON RSCAD

4.1 Introduction

Various simulation technologies are used to model and simulate power system investigations. This is a more efficient way to solve mathematical problems than the old-fashioned way of doing computations by hand. In this chapter, a power network is constructed using the Real-time Simulator Computer-Aided Design (RSCAD) software program. The network contingencies are simulated using this software package. The contingencies include a sudden increase in load and a loss of generating units.

Real-time collaboration is possible between Real-Time Digital Simulator (RTDS) and the commercial software platform RSCAD. RTDS can run, compute, and execute the network at the same time step as a traditional clock because to its parallel computing capabilities. From an application perspective, Hardware-In-the-Loop (HIL) research is most common when combined with RSCAD/RTDS (Basumatary & Shukla, 2022).

Power system components in RSCAD include traveling wave transmission lines and cables (including frequency-dependent models); synchronous and induction machines; saturation transformers; renewable energy; series and static VAR compensation; instrument transformers; and average models of power electronic converters. Researchers can begin, pause, and engage with the simulation in real time by using this software programme. Run simulations, apply errors, and dynamically modify parameters. Easy data annotation and storage.

This chapter seeks to illustrate the need of maintaining sufficient operating reserves of active power, since these can assist in preserving frequency stability in the event of a variety of disturbances in the power system network, such as an abrupt loss of generator power or an increase in load demand. Accurate results and understandable conclusions are a prerequisite for power system engineering investigations. Consequently, a modified IEEE 9 bus network is modelled in the RSCAD software program in order to carry out the event analysis and comprehend the power system operation for the case studies. According to the flowchart displayed in Figure 4.1 below, the analysis is carried out.

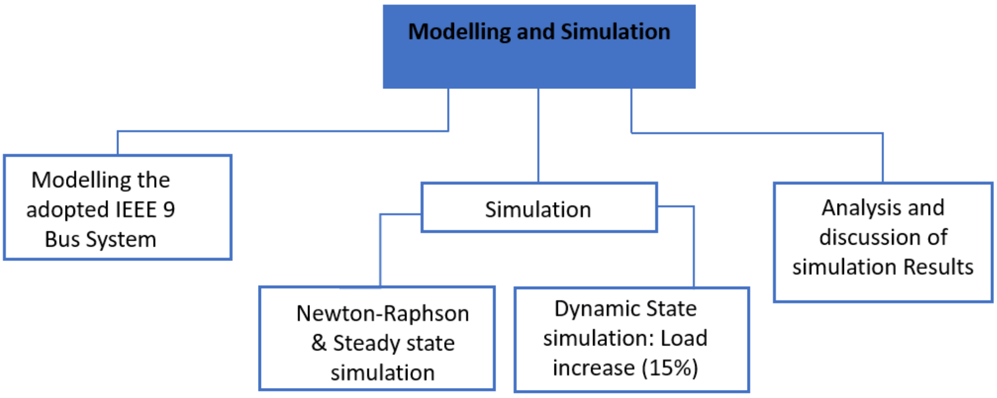


Figure 4.1: Flowchart showing steps followed in the analysis of this chapter

The IEEE 9 bus system network consists of the following interconnected components:

- 6 transmission lines
- 3 transformers
- 3 P-Q loads
- 3 synchronous generators
- 6 HV busbars and 3 MV busbars (9 in total)

In accordance with the South African Transmission and Distribution grid code, IEEE, and IEC standards, the IEEE 9 bus power system has been adjusted to maintain a system frequency of 50 Hz. The schematic of the adopted IEEE 9 bus power system, complete with all of its parts, is displayed in Figure 4.2 below. Section 4.2 below models these components.

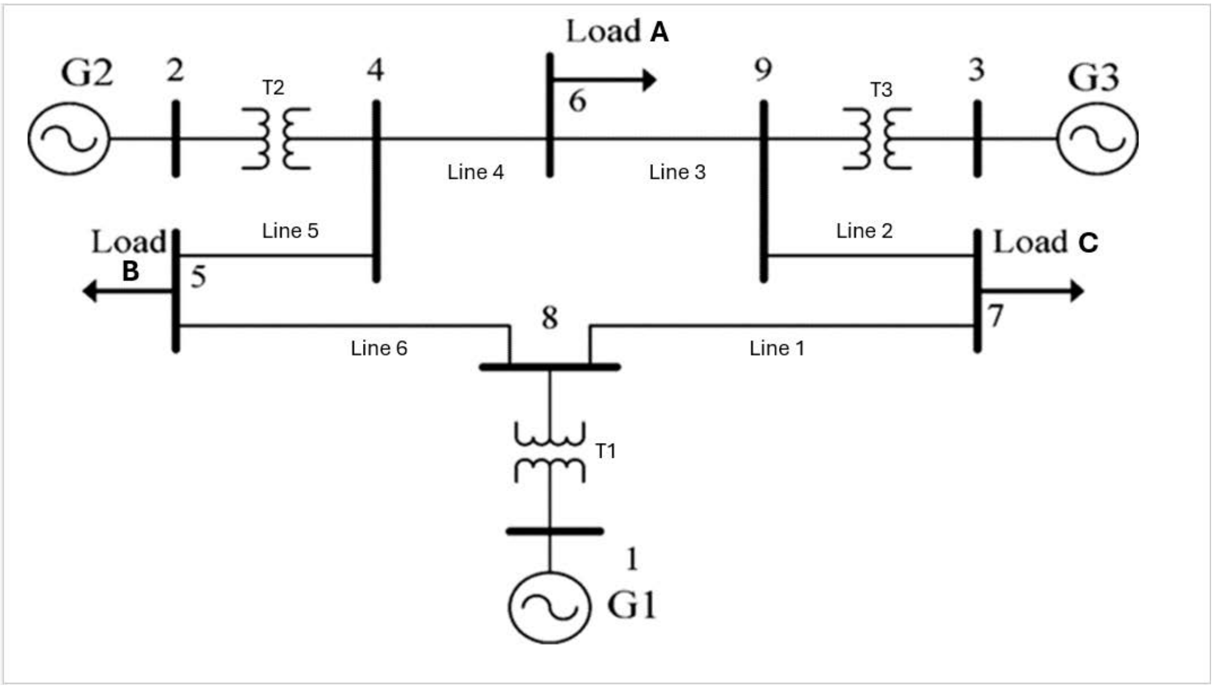


Figure 4.2: IEEE 9 bus power system network

4.2 Modelling of the modified IEEE 9 bus system

Reactive power compensators, composite loads, transmission lines, and generators are some of the parts that make up the power system. Depending on the application, these components may have different configurations. Since the chosen IEEE 9 bus network model is general and appropriate for voltage stability research, it was necessary to modify the load modeling to make it frequency dependent in order to meet the study's goals. Investigating the power system's frequency stability in various scenarios is the goal of this. Unlike voltage, the components of the power system and related control systems required to be modeled to react rapidly to frequency disrupting events.

Table 4.1: Synchronous generators data

Generator	Active power	Reactive power	Stator voltage
G1	71.6 MW	27 Mvar	16.5 kV
G2	163 MW	6.7 Mvar	18 kV
G3	85 MW	-10.9 Mvar	13.8 kV

Table 4.1 above shows the data for each synchronous generator that is a component of the IEEE 9 bus system. The total amount of active power that all three synchronous generators can produce at once is 319.6 MW. Figure 4.3 below displays the synchronous generator model that was created using RSCAD. The synchronous generator has a governor and an excitation system.

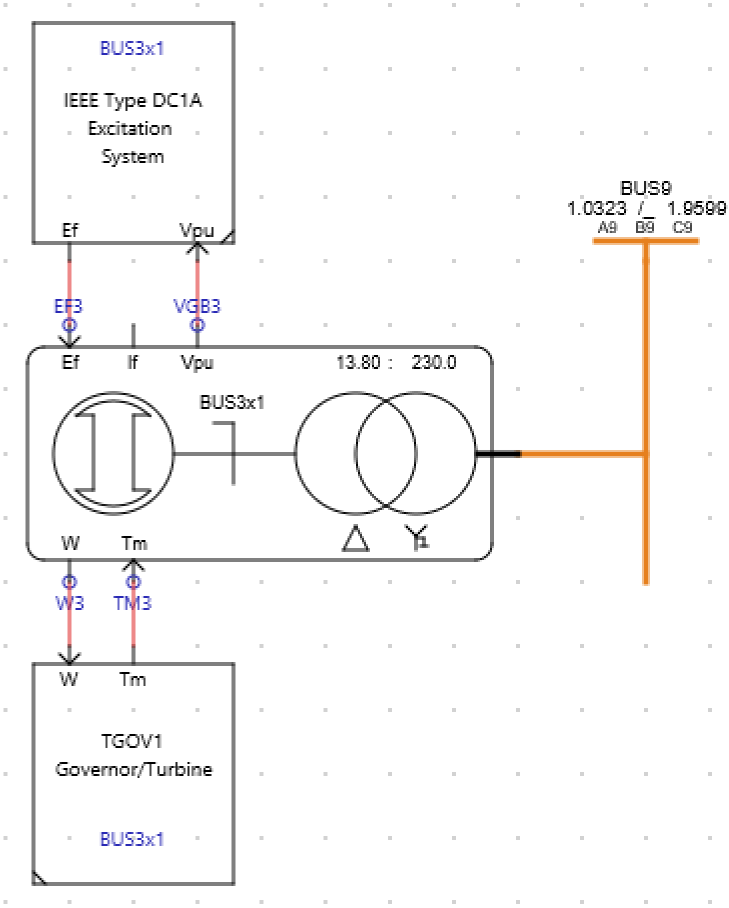


Figure 4.3: Synchronous generator model on RSCAD

As it can be seen in Figure 4.3 above, the transformers are modelled as if they are part of the synchronous generator. There is an internal busbar which connects the two components. All three transformers are used as step-up transformers which feed into the ring feed system. The data of the three transformers is shown in Table 4.2 below.

Table 4.2: Transformer data

Transformer	LV	HV	MVA
T1	16.5 kV	230 kV	100 MVA
T2	18 kV	230 kV	100 MVA
T3	13.8 kV	230 kV	100 MVA

Table 4.3: Load data

Load	Active power	Reactive power
A	100 MW	35 MVAr
B	125 MW	50 MVAr
C	90 MW	30 Mvar

The adopted IEEE 9 bus system comprises three dynamic loads situated in three different busbars. The active power and reactive power ratings of the loads are stipulated in Table 4.3 above. The RSCAD load model, as shown in Figure 4.4 below, was modified in such a way that it can be controlled in real time during the simulation.

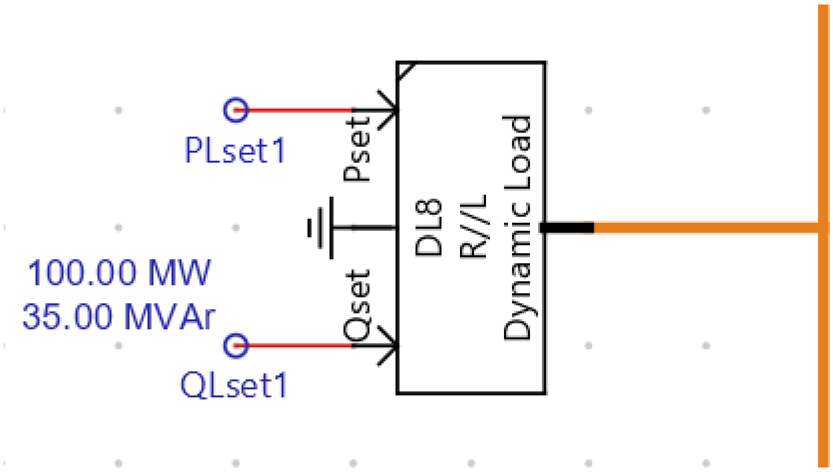


Figure 4.4: **RSCAD load model**

The table below, Table 4.4, depicts the transmission line data for all 6 transmission lines which form part of the IEEE 9 bus system. All transmission lines are operating at 230 kV.

Table 4.4: **Transmission line data**

Line	Voltage	Pos. Seq. R	Pos. Seq. XL	Pos. Seq. XC	Zero. Seq. R	Zero. Seq. XL	Zero. Seq. XC
Line 1	230 kV	0.01005	1.08521	5.688921	0.150751	0.298234	10.158787
Line 2	230 kV	0.017083	1.092216	6.336801	0.256241	0.322756	11.315716
Line 3	230 kV	0.032533	1.162281	3.28151	0.487999	0.567985	5.85984
Line 4	230 kV	0.039806	1.171651	2.807618	0.597084	0.60078	5.013604
Line 5	230 kV	0.00853	1.072127	6.717421	0.127957	0.252445	11.995395
Line 6	230 kV	0.011984	1.10115	4.793121	0.179761	0.354027	8.559145

The updated IEEE 9 bus power system network as set up on the RSCAD platform is shown in Figure 4.5 below. All the equipment has been modelled and configured as per the specifications in the above sections. The model shown in Figure 4.5 below was configured on the RSCAD Draft where the users of the simulation package can only run a load/power flow. For real-time monitoring, RSCAD Runtime is used. RSCAD Runtime allows users to change some components such as the load in real time whilst the simulation is running to simulate different scenarios like for example a sudden increase in load, sudden generator loss, sudden drop in wind speed, etc.

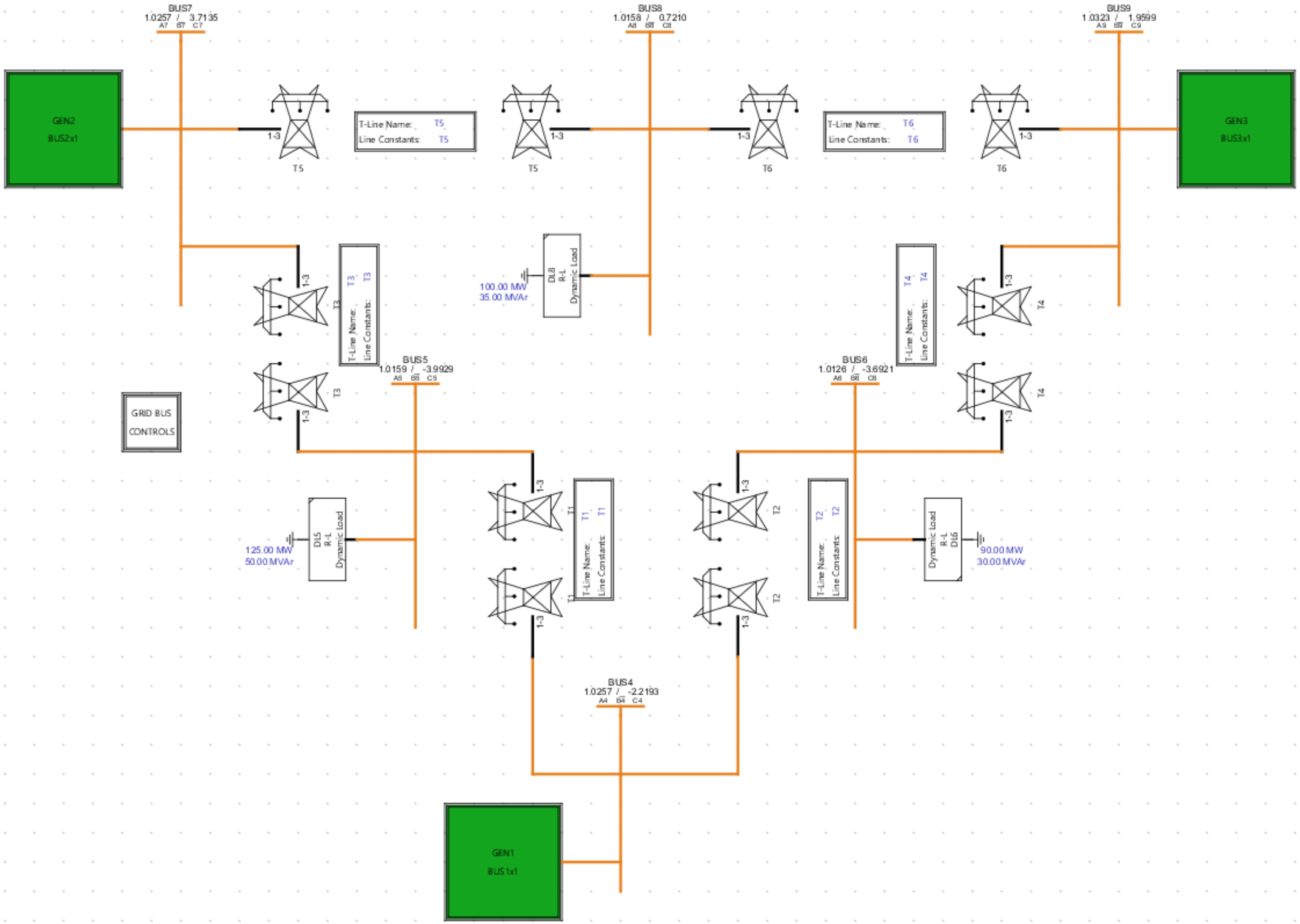


Figure 4.5: Modified IEEE 9 bus network in a de-energized state

The power system analysis is an extensive study that concentrates on the ways in which various characteristics impact the network's stability. The analysis's dynamic and steady-state states must be assessed. The analysis is in a steady condition when the power system is not interrupted. Because generated active power in a steady state equals the sum of active load power demand and system power losses, the system frequency is set at 50 Hz. Power flow analysis is the method used to conduct research at this level.

However, when the system is subjected to disruptions from changes in load, planned and unplanned power outages brought on by faults, and equipment maintenance, it is said to be in a dynamic state. The power system disturbance will result in variations in voltage and frequency. The disturbance's type and strength have an impact on how much the frequency and voltage deviation fluctuate. Dynamic-state analysis is the process of carrying out these kinds of situations. Nonetheless, the system is examined in steady-state before any disturbance research is done, and dynamic analysis is then completed.

4.3 Steady-state simulation and results analysis

Power flow equations are utilized in steady-state analysis to calculate the transmission line currents and bus voltage magnitudes and angles. The stringent grid code limitations must be adhered to by the bus voltages. The power system has an acceptable standard operating voltage that falls between 0.95 and 1.05pu. The frequency range for continuous operation that is permitted is 49.5 Hz to 50.5 Hz.

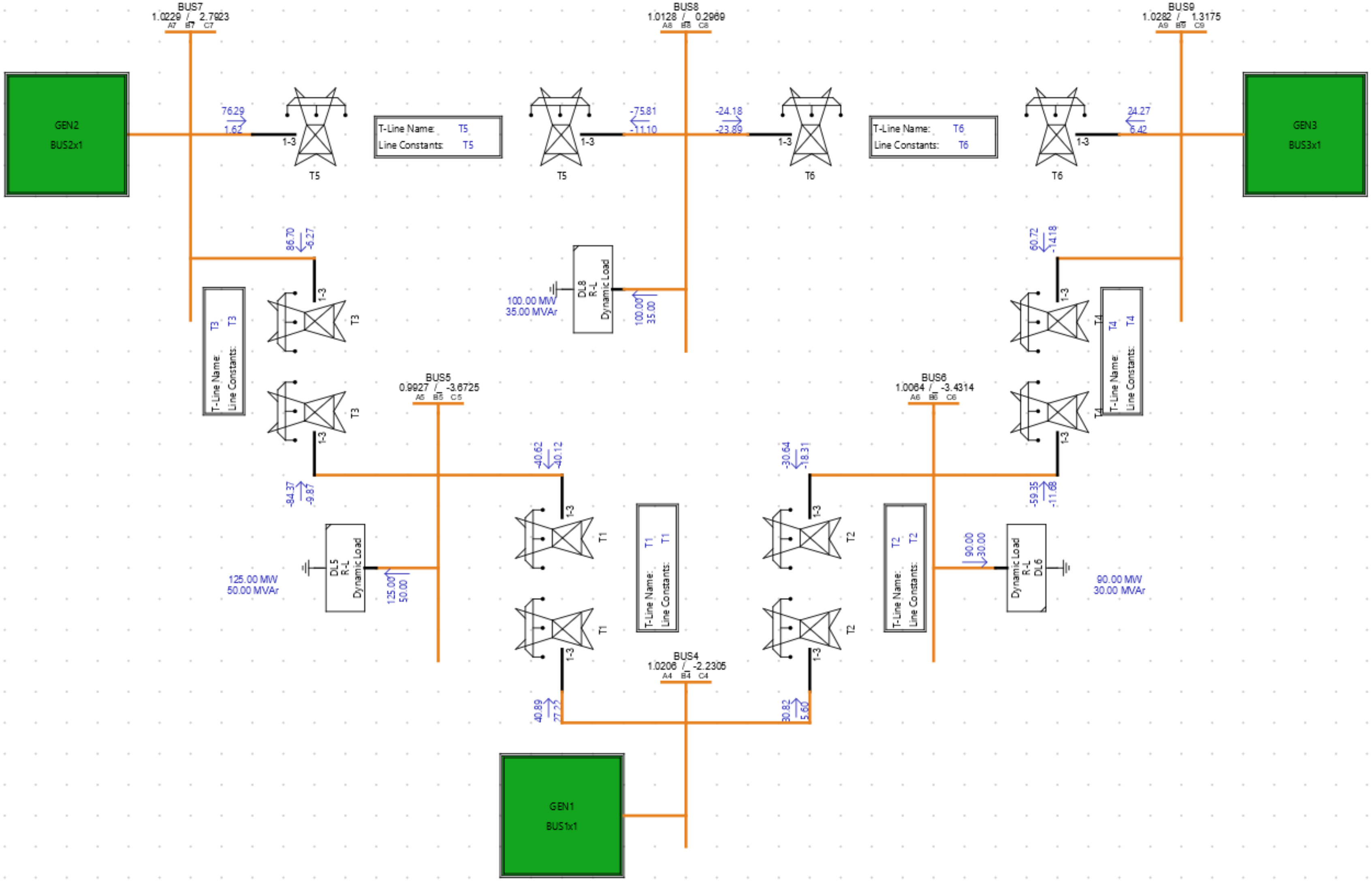


Figure 4.6: Power flow results

The steady-state analysis can also be performed using the RSCAD runtime simulation option. The significance of this analysis is to prove that the power system network developed is stable (generation and load demand are balanced) before the contingencies are applied. Grid bus voltage, generation supply, load demand, and system frequency are monitored. Figure 4.7 below shows results for the total generation supply, total system load demand, grid bus voltage, and network frequency during steady-state analysis. Figure 4.9 below shows the waveform of the system frequency at a steady state which is stable at 50Hz. According to the results, the total generation and total load (including losses) are balanced at 319.9MW which leads to a stable frequency of 50Hz. The grid bus voltage is stable between 0.9913 and 1.026 per unit.

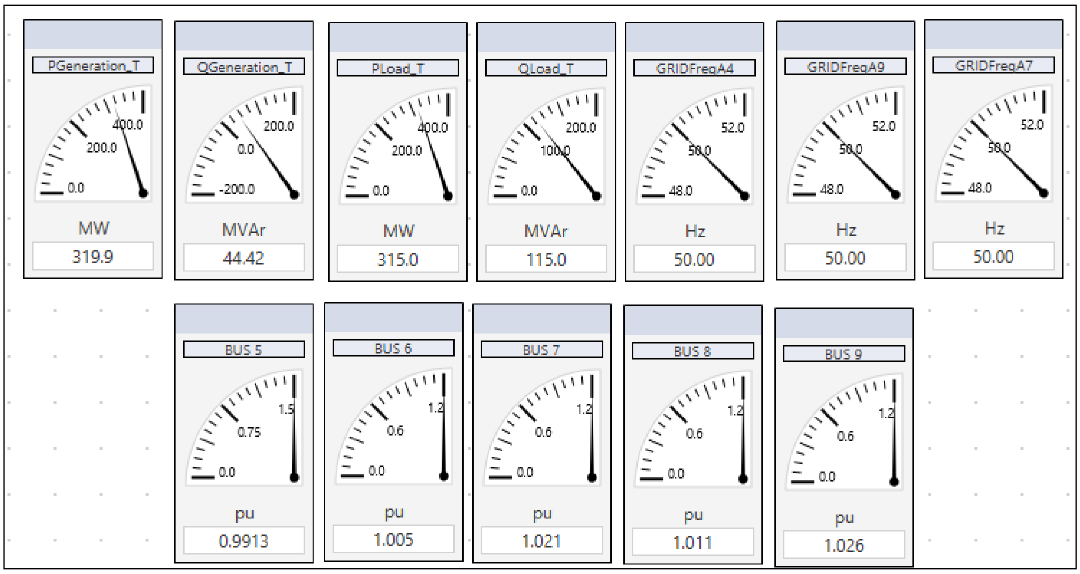


Figure 4.7: Steady-state generation supply, bus voltages, load demand, and system frequency

By deducting the load demand power from the total generation supply, one may calculate the power loss. The power losses amount to 4.9 megawatts. The active power and reactive power readings of every synchronous generator at steady state are shown in the following diagram, Figure 4.8.

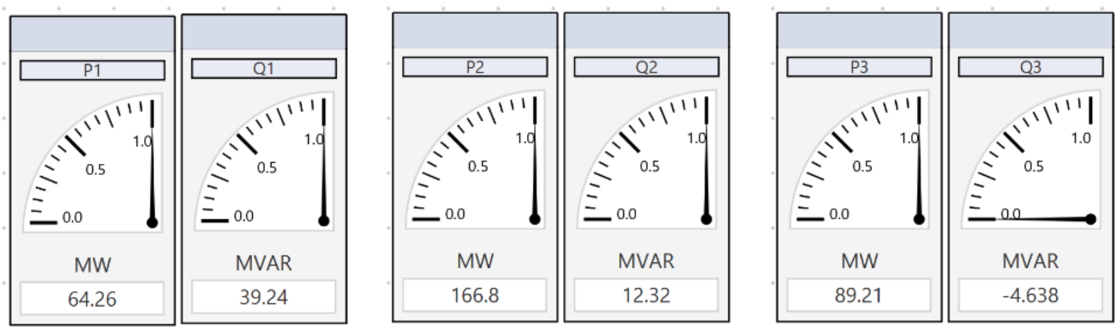


Figure 4.8: P and Q steady state readings for all three generators

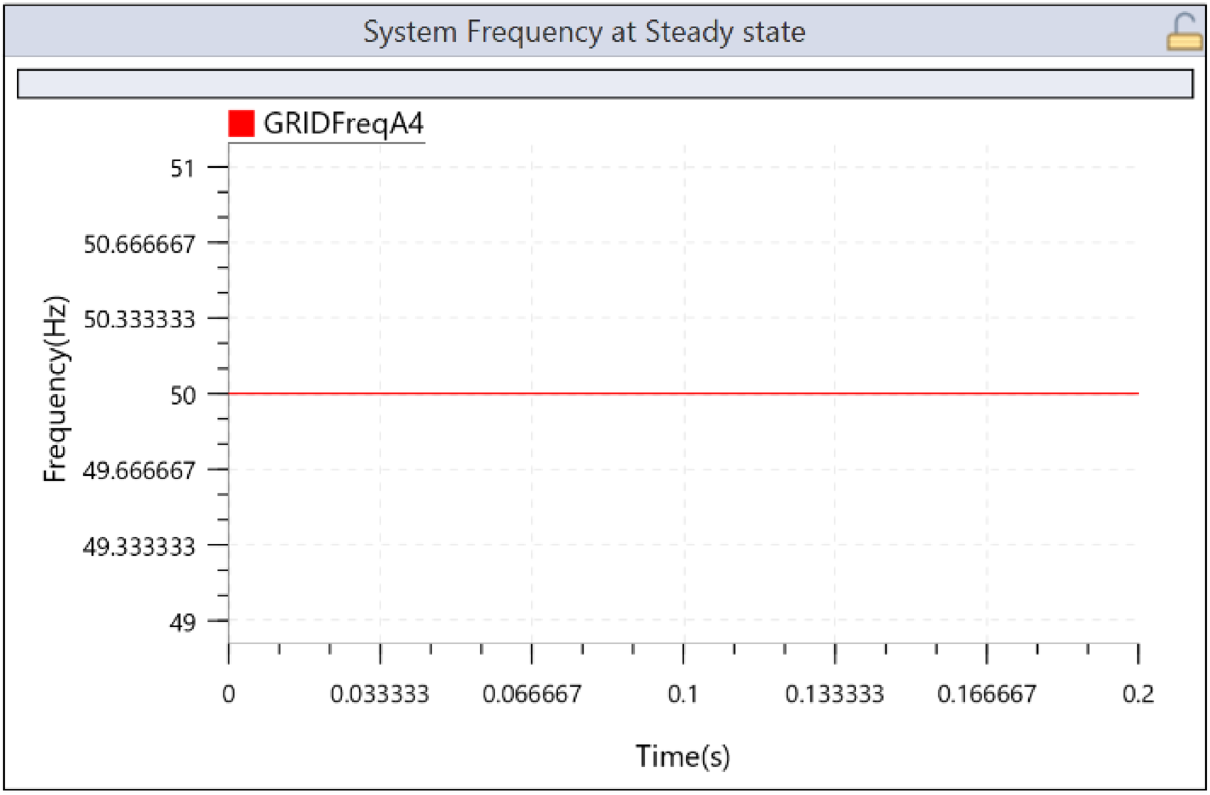


Figure 4.9: System frequency at steady state

The busbar voltages which were measured at steady state are tabulated in Table 4.5 below. All voltages are within the limit of 0.95 pu to 1.05 pu.

Table 4.5: Busbar voltages at steady state

Busbar	Per unit voltage
Bus 1	1.039
Bus 2	1.024
Bus 3	1.022
Bus 4	1.020
Bus 5	0.9913
Bus 6	1.005
Bus 7	1.021
Bus 8	1.011
Bus 9	1.026

4.4 Dynamic state simulation and results analysis

The purpose of this investigation is to examine how the system frequency behaved when the load suddenly rose. Additionally, to demonstrate the necessity of active power operational reserves for maintaining the power system's stability. When adequate operating reserves are kept, mechanisms can be put in place to compensate for any imbalances in the grid during normal and abnormal grid contingencies such as the increase in load demand or a sudden generator loss. If the frequency lowers when the load demand exceeds the power system's generation capacity, it could seriously affect the grid if it is not promptly addressed. The South African power producer, Eskom, has in many cases resorted to load shedding due to not having enough operating reserves to compensate during sudden load increases.

4.4.1 Case Study 1-Load demand increased by 15%

The implementation of the load demand contingency on RSCAD is achieved using a load scheduler. In the load scheduler component, the load multiplier and the time at which the load demand increase should occur can be defined. The type of load demand component (active and reactive components) increase has its scheduler. Figure 4.13 below shows the configuration of the load scheduler as modelled on RSCAD. The load scheduler shown in Figure 4.13 below is configured in such a way that during a dynamic state analysis, it will increase the system load demand by 15% in steps of 1% over a period of 150s (1% per 10s). The load demand increase is done on both the active and the reactive components of the loads. The aim of applying this contingency is to assess the response of the grid, system frequency to be specific, during a dynamic state condition.

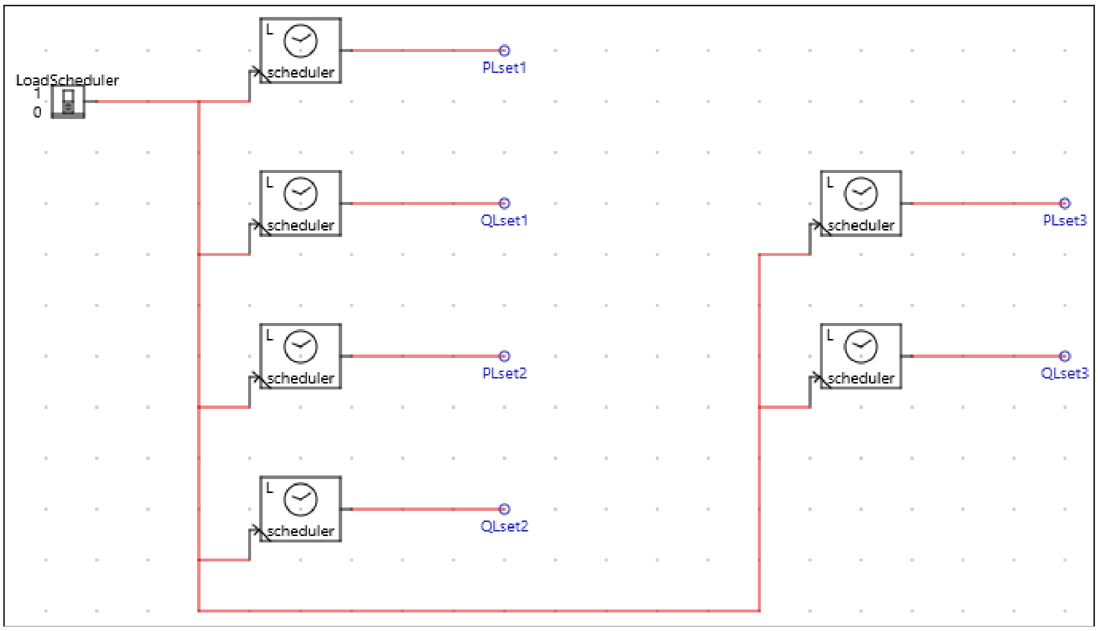
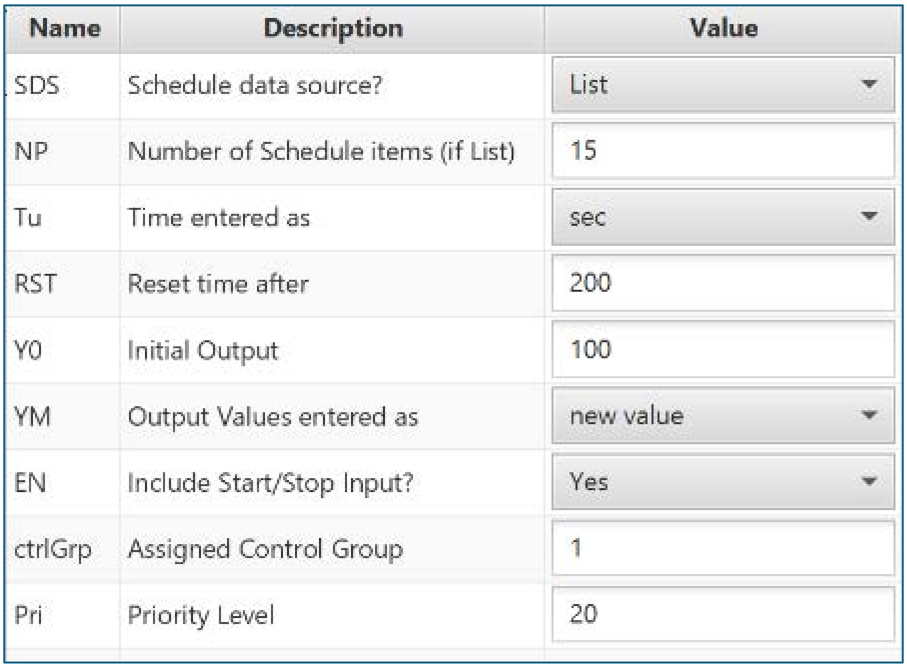


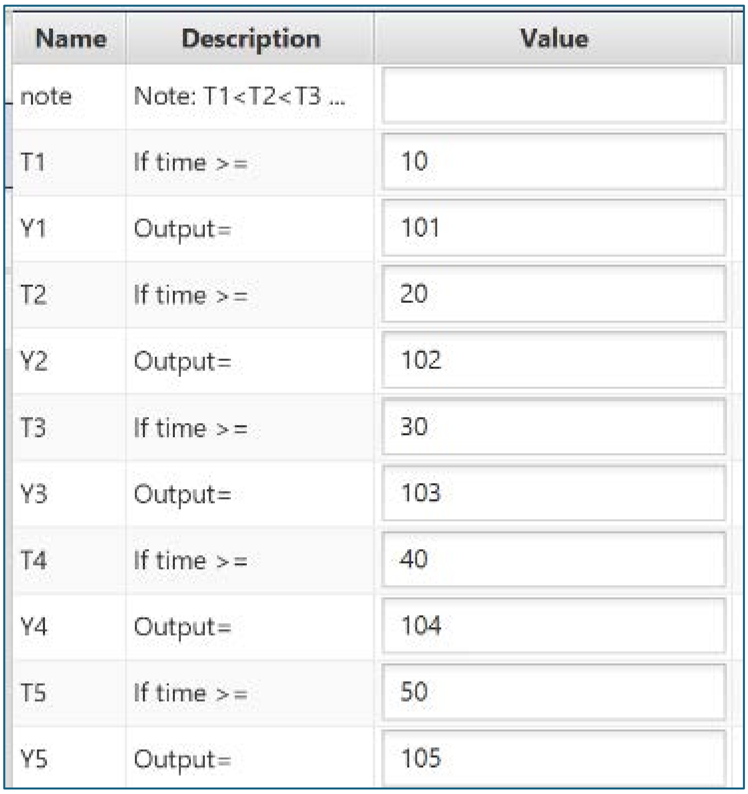
Figure 4.10: Load scheduler as modelled on RSCAD

The configuration of the load scheduler is shown in Figure 4.11 below. The load scheduler is configured to have 15 scheduled items where each item will represent a 1% increase on the load. The 15 schedules items will equate to a 15% increase on the load. In Figure 4.12 below, five scheduled items are shown as an example. If for example the initial active power is 100 MW, 15% of that will be 15 MW which means that in each item, the active power will increase by 1 MW.



Name	Description	Value
SDS	Schedule data source?	List
NP	Number of Schedule items (if List)	15
Tu	Time entered as	sec
RST	Reset time after	200
Y0	Initial Output	100
YM	Output Values entered as	new value
EN	Include Start/Stop Input?	Yes
ctrlGrp	Assigned Control Group	1
Pri	Priority Level	20

Figure 4.11: Load scheduler configuration



Name	Description	Value
note	Note: T1<T2<T3 ...	
T1	If time >=	10
Y1	Output=	101
T2	If time >=	20
Y2	Output=	102
T3	If time >=	30
Y3	Output=	103
T4	If time >=	40
Y4	Output=	104
T5	If time >=	50
Y5	Output=	105

Figure 4.12: Output scheduling

The outcomes of the power system's monitored signals following the load demand increase contingency are displayed in Figure 4.13 below. The system frequency decreased from 50Hz to 49.59Hz due to the load demand increase contingency. Because of the rise in load demand from 315 MW to 362.2 MW, the total generation supply increased from 319.9 MW to 368.7 MW. With a recorded value of 0.9711pu, Bus 5 voltage is considered to be the lowest voltage bus in the system.

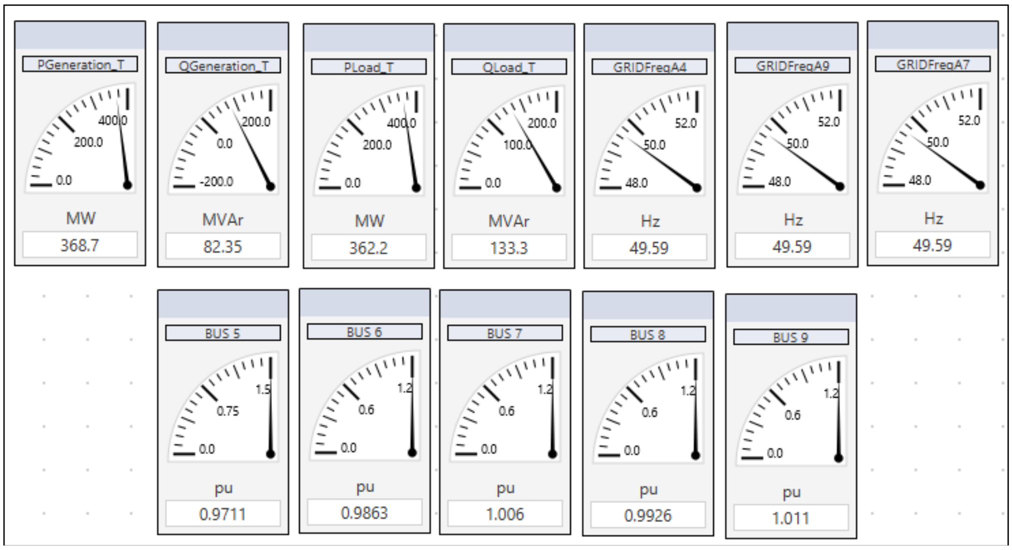


Figure 4.13: System monitored variables after a 15% load demand increase

The following Figure 4.14 shows a graphic representation of the load demand rise for Load A. Prior to the load increase, load A's active power and reactive power were measured at 100 MW and 35 Mvar, respectively; following the load increase, these values were recorded at 115 MW and 40.25 Mvar, respectively.

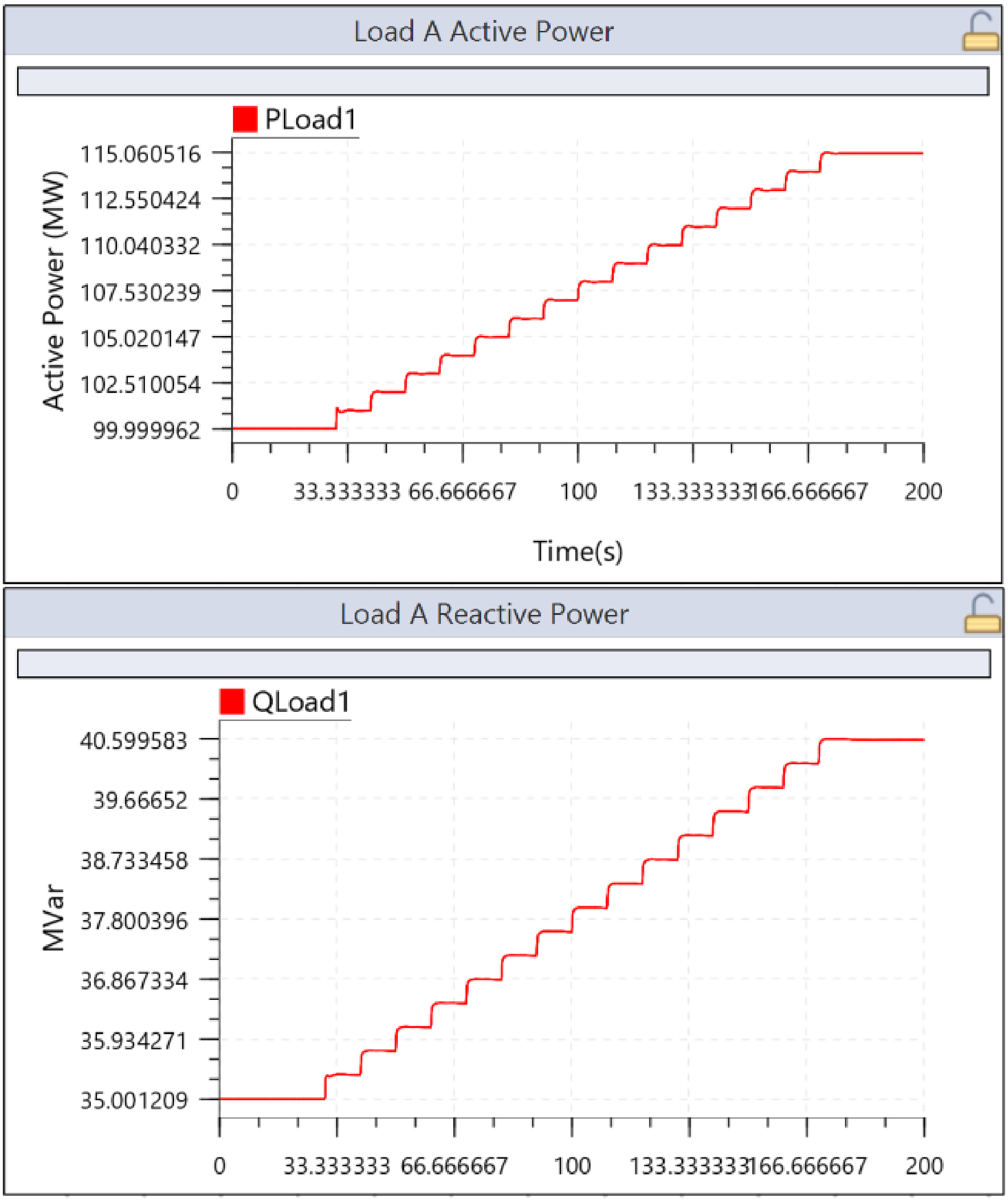


Figure 4.14: **P and Q results for Load A at dynamic state**

The following Figure 4.15 shows a graphic representation of the load demand rise for Load B. Prior to the load increase, load B's active power and reactive power were measured at 125 MW and 50 Mvar, respectively; following the load increase, these values were measured at 143.8 MW and 58 Mvar, respectively.

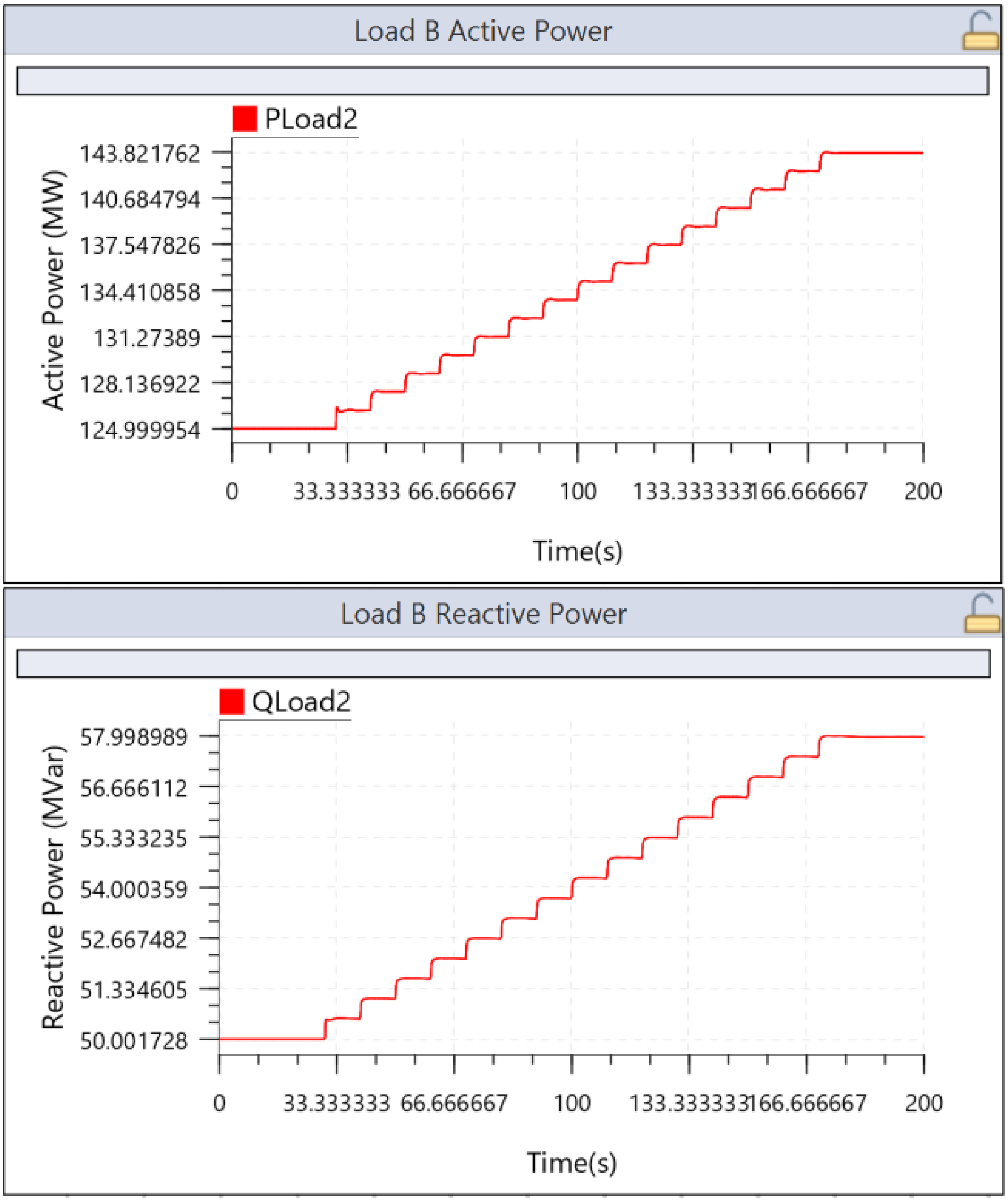


Figure 4.15: P and Q results for Load B at dynamic state

The following Figure 4.16 shows a graphic representation of the load demand rise for Load C. Prior to the load increase, load C's active power and reactive power were measured at 90 MW and 30 Mvar, respectively; following the load increase, these values were recorded at 103.55 MW and 34.8 Mvar, respectively.

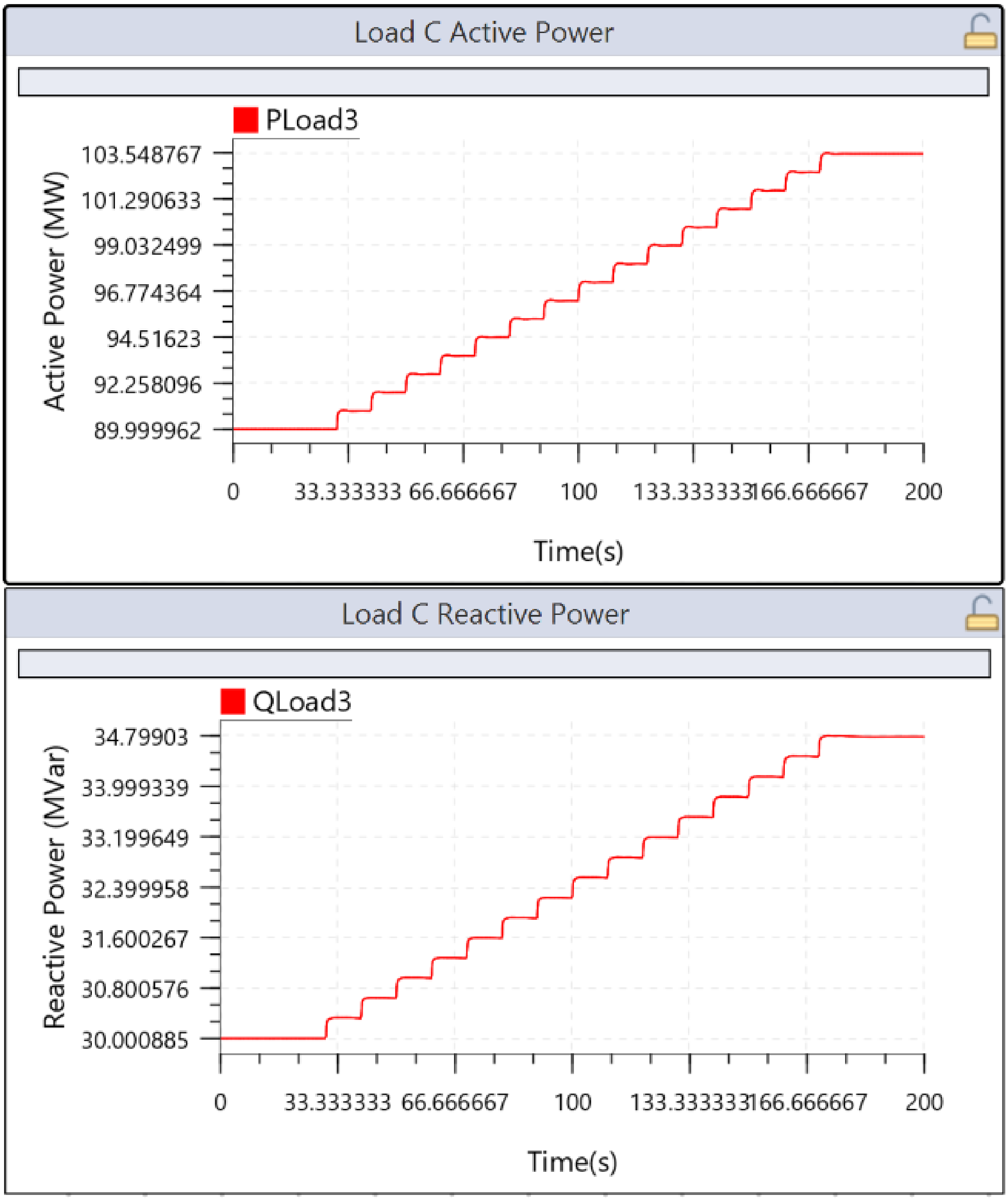


Figure 4.16: P and Q results for Load C at dynamic state

Figure 4.17 below displays the entire load demand waveform that was captured during the dynamic state simulation. According to the wattage measurement meter in Figure 4.13 above, the load ramping begins at an initial system loading of 315 MW and climbs by 1% steps to 15%, or 362.25 MW. Reactive power was recorded as 115 MVArs in Figure 4.17 below prior to the application of the load demand increase contingency, and it was recorded as 133.37 MVArs following the load demand increase.

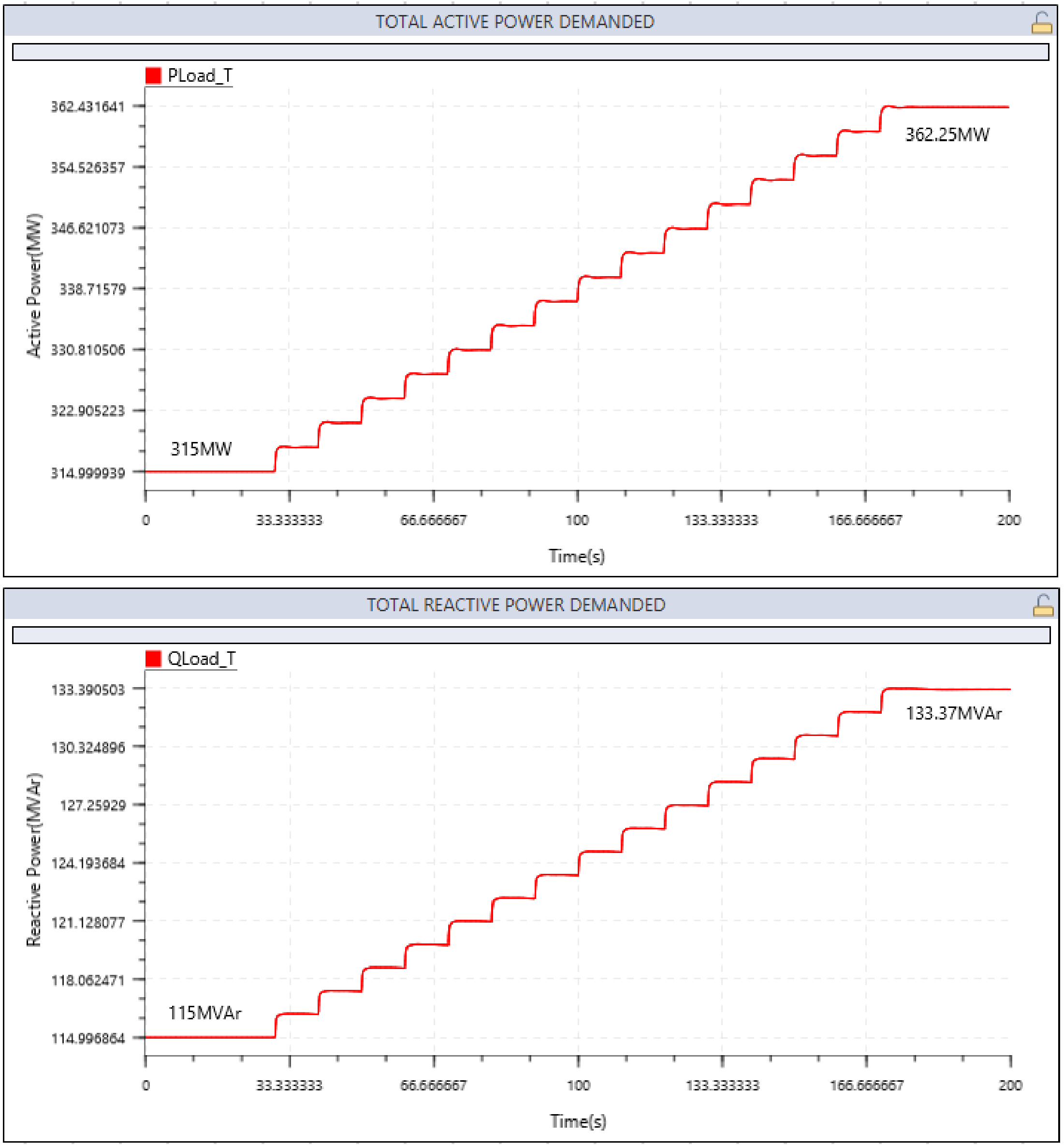


Figure 4.17: Total load demand after 15% load demand increase

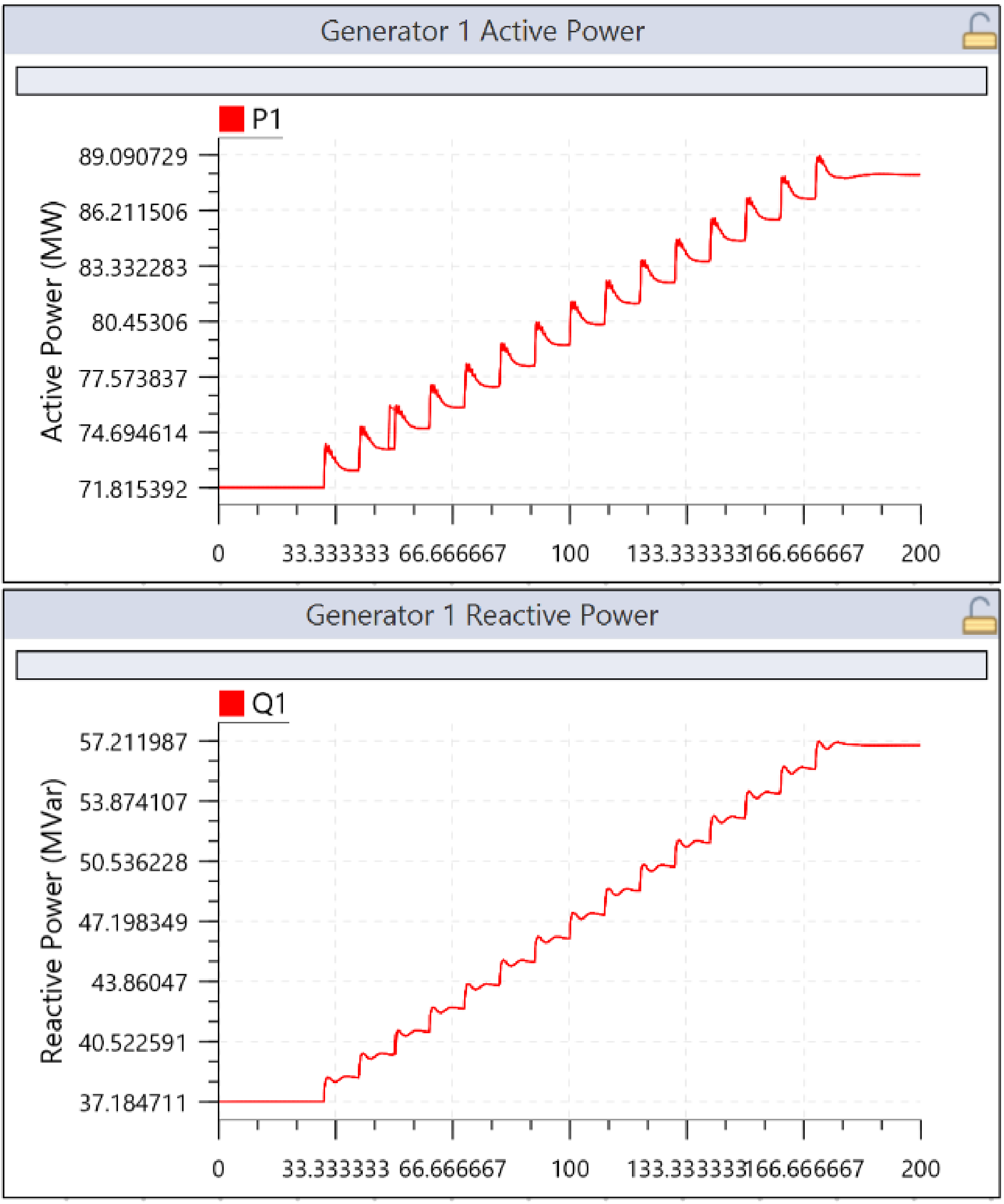


Figure 4.18: **P and Q waveform for Generator 1 during the dynamic state**

As shown in the diagram above, Figure 4.18, when the load was ramped up by 15%, the active power generated by Generator 1 increased from 71.82 MW to 88.32 MW and reactive power from 37.18 MVars to 57.21 MVars, respectively. The plot of the generator 1 supply for both active and reactive generation power is displayed in Figure 4.18 diagram above, prior to, during, and following the rise in load demand.

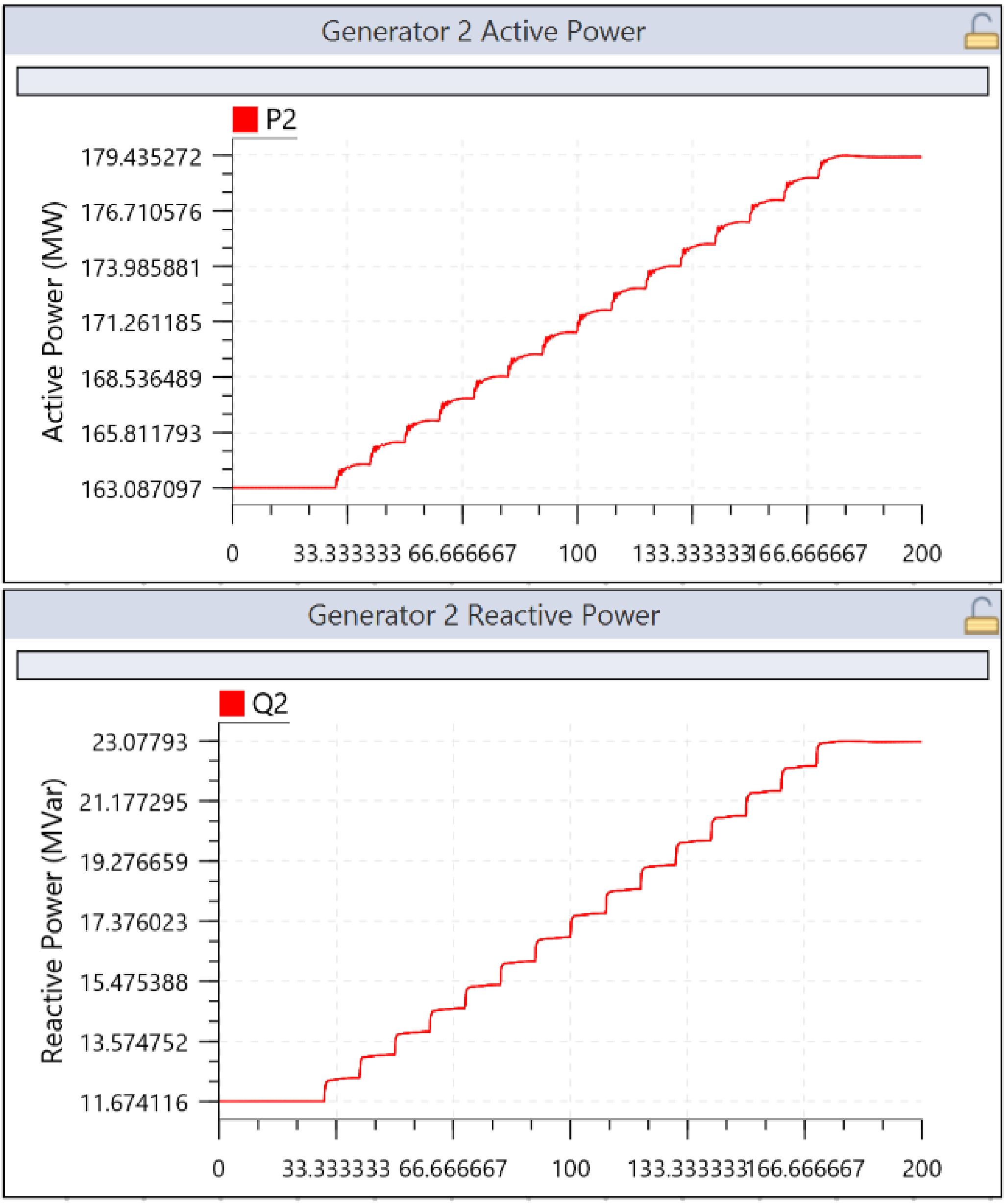


Figure 4.19: P and Q waveform for Generator 2 during the dynamic state

As shown in the diagram above, Figure 4.19, when the load was ramped up by 15%, the active power generated by Generator 2 increased from 163.09 MW to 179.44 MW and reactive power from 11.67 MVars to 23.08 MVars, respectively. The plot of the generator 2 supply for both active and reactive generation power is displayed in the above Figure 4.19 figure prior to, during, and following the rise in load demand.

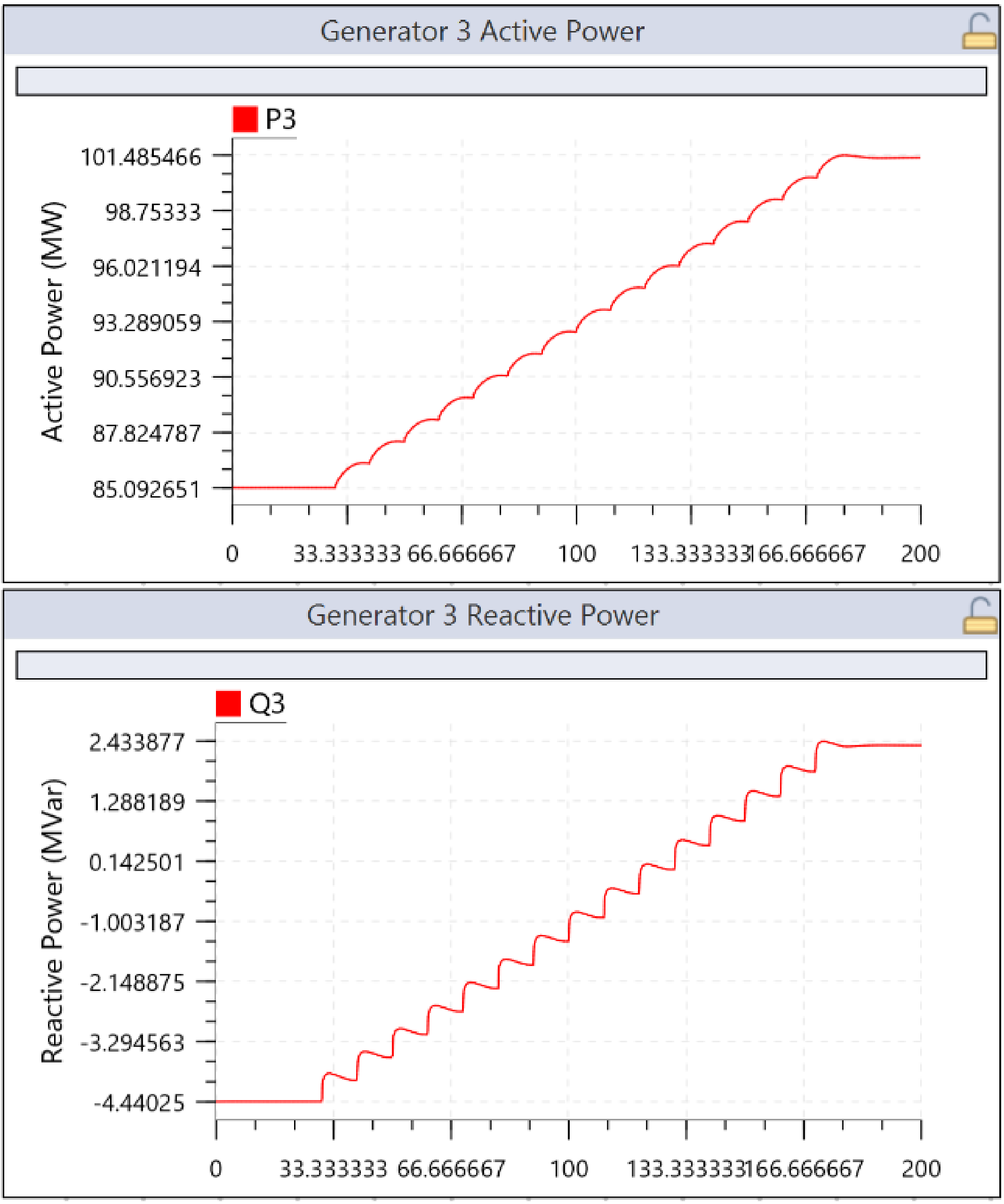


Figure 4.20: **P and Q waveforms for Generator 3 during the dynamic state**

As shown in the diagram above, Figure 4.20, when the load was ramped up by 15%, the active power generated by Generator 3 increased from 85.09 MW to 101.48 MW and reactive power from -4.44 MVars to 2.43 MVars, respectively. The plot of the generator 3 supply for both active and reactive generation power is displayed in Figure 4.20 figure above, both before and after the load demand increase.

The picture below, Figure 4.21, illustrates how the total generation supply active power climbed from 319.94MW to 368.76MW and the reactive power increased from 44.42MVars to 82.54MVars, respectively, when the demand was scaled up by 15%. The plot of the total generating supply for both active and reactive generation power before, during, and after the rise in load demand is displayed in Figure 4.21 graphic below.

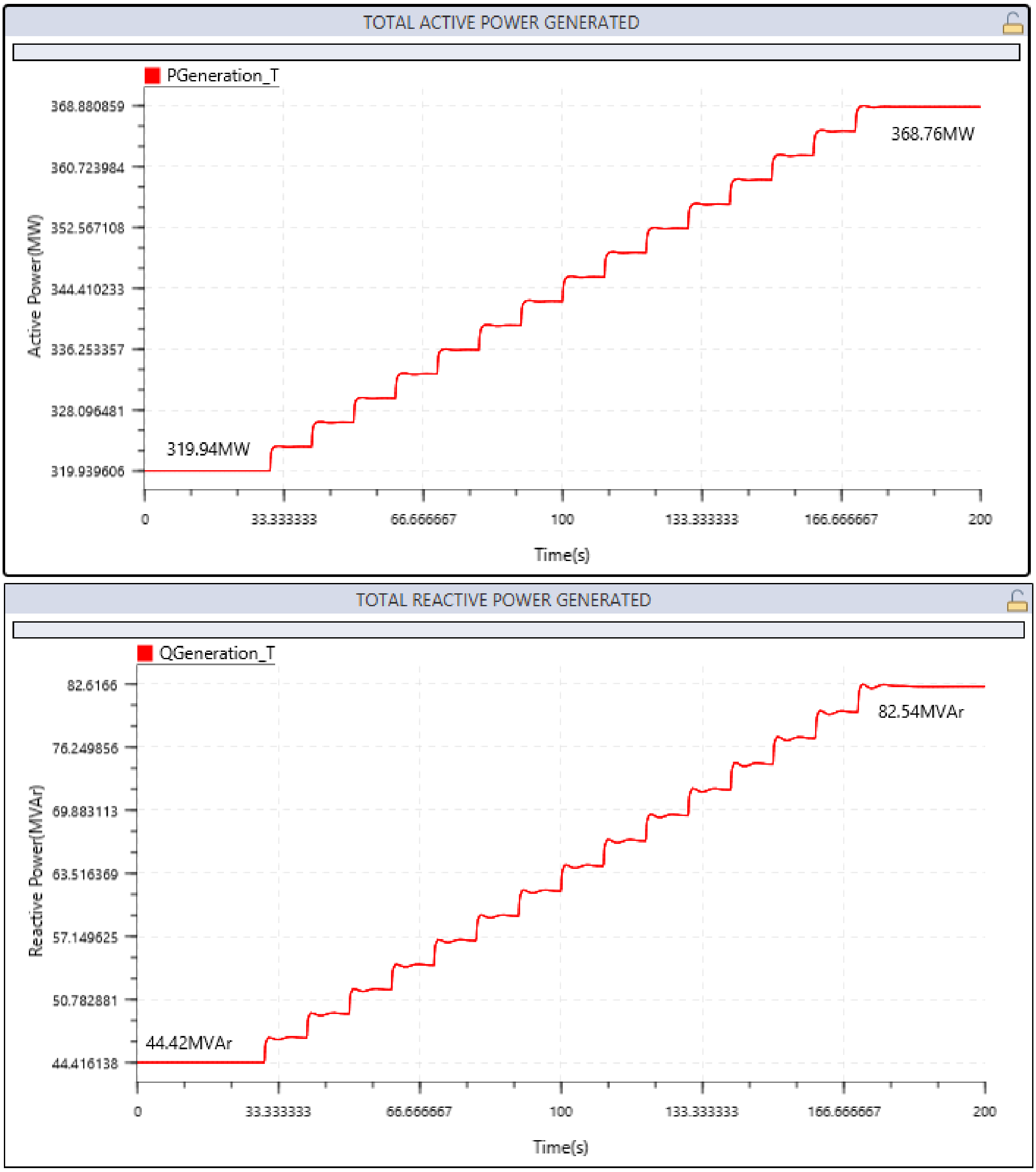


Figure 4.21: Total generation supply after 15% load demand increase

In this thesis, the necessary active power is defined as the quantity of active power needed to maintain a balance between supply and demand. The goal of this thesis is to supply this necessary active power using battery energy storage and wind energy systems' operating reserves. Figure 4.22, the diagram below, displays a waveform of the active power needed to keep the grid balanced as the load grows. The needed active power before the load is increased is 0.306 MW, which is not substantial enough to change the voltage or frequency. The amount of active power needed to balance the grid when the load is increased by 15% is 48.52 MW.

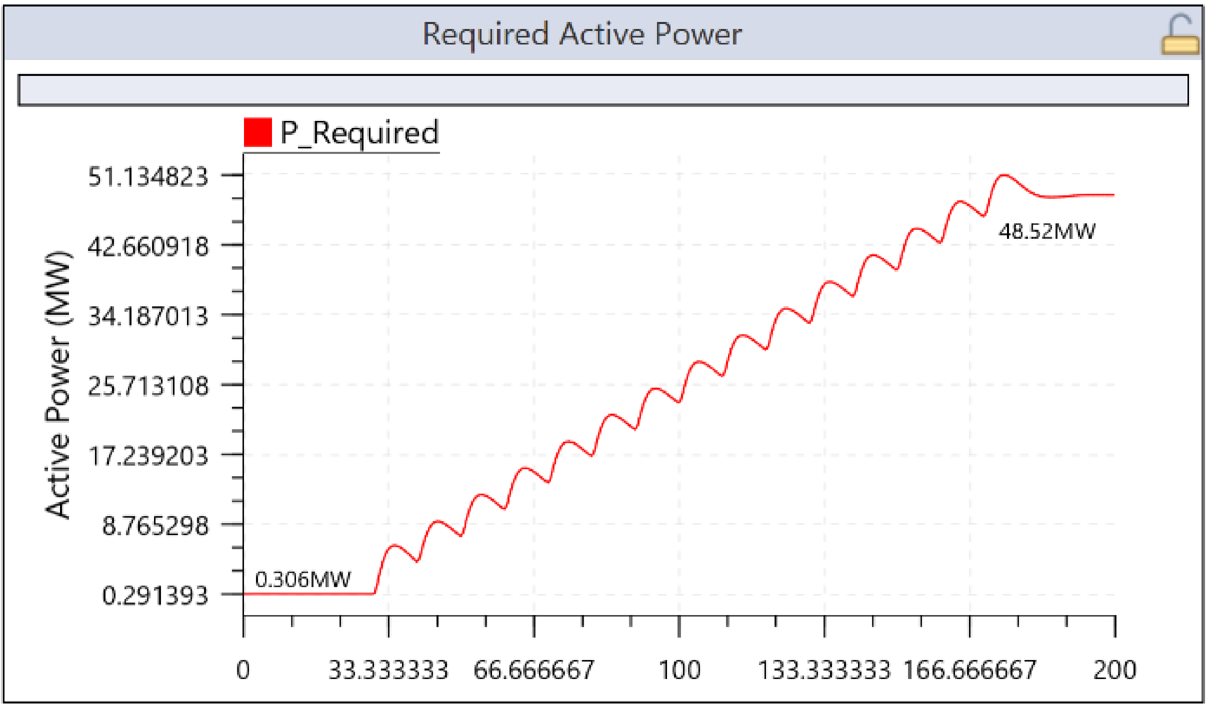


Figure 4.22: Waveform of the required active power to balance the grid

The system frequency dropped from 50Hz at steady state, which was initially seen, partly due to an increase in load demand. Following the load demand increase contingency, 49.59 Hz was recorded as the system frequency. While this system frequency falls between the acceptable operating frequency range (49.5Hz and 50.5Hz) in South Africa's power system grid code standard, operating at 49.59Hz would be dangerous since further grid disturbances might seriously affect the network. The findings of the system frequency are displayed in Figure 4.23 below.

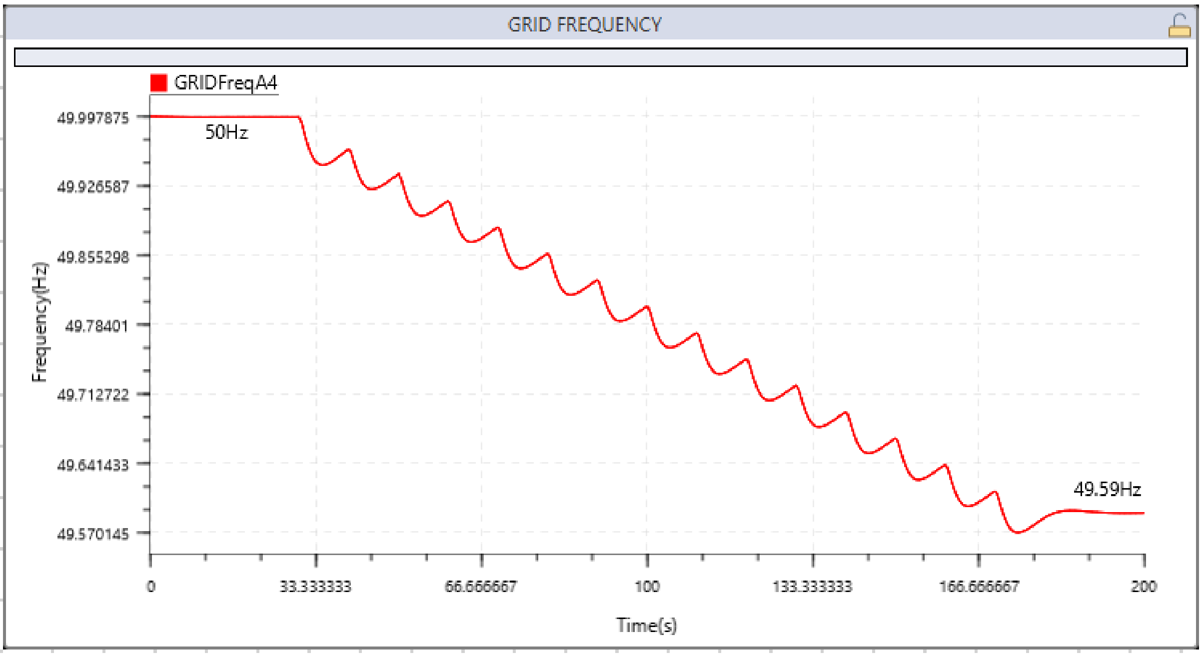


Figure 4.23: System frequency after 15% load demand increase

The simulated load increase did not have much of an impact on the busbar voltages. In Table 4.6 below, the readings of the busbar voltages before and after the load increase are recorded. As it can be seen, the voltages after the load increase are within the acceptable range of 0.95 pu and 1.05 pu. The load increase led to a voltage drop in all busbars. The most affected busbar is Bus 5 which dropped to a value of 0.9711 pu.

Table 4.6: Busbar voltage comparison before and after the load increase

Busbar	Voltage before	Voltage after
Bus 1	1.039	1.038
Bus 2	1.024	1.013
Bus 3	1.022	1.011
Bus 4	1.020	1.007
Bus 5	0.9913	0.9711
Bus 6	1.005	0.9864
Bus 7	1.021	1.007
Bus 8	1.011	0.9981
Bus 9	1.026	1.014

The waveforms for total active power generated, total active power demanded, total active power required, and the impact on system frequency are displayed in the diagram below, Figure 4.24. An overview of the dynamic state analysis conducted prior to the active power control loop's implementation is given in this diagram. Due to the generators running above their rated values as a result of the 15% increase in load, frequency dropped. A waveform representing the necessary active power is also included; this represents the quantity of active power needed to maintain the system frequency at 50 Hz while balancing supply and demand.

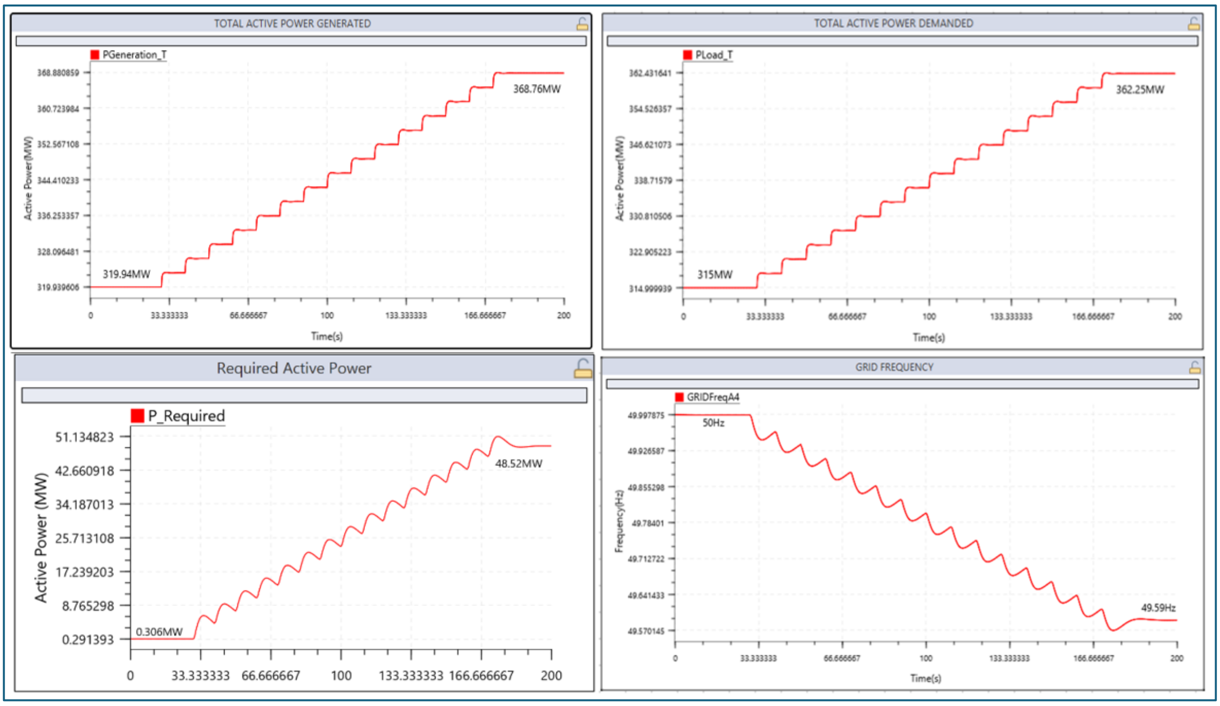


Figure 4.24: Effect of a 15% load increase on generation and frequency

4.5 Discussion of results

This section's primary goal is to offer a critique and discussion of every experiment and study conducted in this chapter. A steady-state analysis was carried out in Chapter 4 to demonstrate the power system's stability prior to the implementation of any grid contingencies. In order to demonstrate how an occurrence such as a load demand rise contingency can jeopardize the stability of the power system and how active power reserves are actually necessary to help balance the power system in these situations, a grid contingency was also implemented.

4.5.1 Steady state analysis

After the modification of the IEEE 9 bus system, a steady-state simulation was undertaken. The steady state simulation was executed using both the Newton-Raphson load flow calculation method in RSCAD Draft and via real-time digital simulation (RTDS) in RSCAD Runtime. The steady-state analysis proved that the power system network was stable before the grid contingencies were applied with the system frequency stable at 50Hz.

4.5.2 Dynamic state analysis (pre-implementation of active power control)

The results shown in Table 4.5 below were recorded before a load demand increase and after the load demand increase was implemented. The weakest busbar in terms of voltage was discovered to be busbar 5. Before the execution of the load event, the voltage at bus 5 was 0.9913pu, and after the load demand increased, the voltage on bus 5 was 0.9711pu. The power system grid frequency before the load demand increase executed was at its nominal value of 50Hz. After the load demand increased, the frequency dropped to 49.59Hz. After the 15% load demand increase, the total load rose from 315MW to 362.25MW and the total generation increased from 319.94MW to a value of 368.76MW.

Table 4.7: **Case study 1 results (before implementation of control techniques)**

<table>
<tr><th colspan="2">Case study name</th><th colspan="2">Aim</th><th colspan="4">Type of disturbance</th></tr>
<tr><td colspan="2">Case study 1</td><td colspan="2">This case study proves that the stability of the grid is compromised when the load demand increases to a value greater than the generation capacity. This study also emphasizes the need for active power operating reserves in the grid.</td><td colspan="4">Load demand increased by 15% in steps of 1%</td></tr>
<tr><th colspan="8">Monitored variables</th></tr>
<tr><th colspan="2">Lowest bus voltage (PU)</th><th colspan="2">System Frequency (Hz)</th><th colspan="2">Total load demand (MW)</th><th colspan="2">Total Generation (MW)</th></tr>
<tr><td>before</td><td>after</td><td>before</td><td>after</td><td>before</td><td>after</td><td>before</td><td>after</td></tr>
<tr><td>0.9913</td><td>0.9711</td><td>50</td><td>49.59</td><td>315</td><td>362.25</td><td>319.94</td><td>368.76</td></tr>
</table>

In this chapter, it was proven that there is a need for active power operating reserves in the power system as grid contingencies like a sudden increase in load demand can lead to a grid imbalance.

4.6 Conclusion

The generation capacity and the load demand need to be always balanced to ensure grid stability. When generation is more than the load demand, this can lead to an increase in system frequency. On the other hand, when the load demand is greater than the generation capacity, this can lead to the system frequency dropping to unacceptable levels. The grid operators need to have solutions in place ready to restore power system balance should predict and unforeseen grid contingencies occur.

From the results of case study 1 which was simulated above to express a dynamic state of the grid, it can be seen that load demand increases lead to drops in frequency. Grid operators need to have active power operating reserves for such conditions that can be dispatched on time to balance the grid before there are any severe consequences. This research study proposes the use of a wind energy system and a battery energy storage system for the provision of active power operating reserves for similar occasions where the sudden changes on the grid and the stability is compromised. The next chapter, Chapter 5, investigates the possible participation of wind energy systems and battery energy storage systems in the provision of active power operating reserves.

CHAPTER FIVE

DEVELOPED ACTIVE POWER CONTROL ALGORITHM FOR THE OPERATION OF THE WES AND BESS UNITS WITHIN THE IEEE 9 BUS SYSTEM.

5.1 Introduction

This chapter models and integrates the battery energy storage system (BESS) and wind energy system (WES) into the grid to supply active power reserves. The control schemes were created using the real-time digital simulation (RTDS) technology, which is also used to interface the BESS and WES to the grid. The effectiveness of the established control systems is evaluated by applying a load demand growth contingency. Thus, it is anticipated that the developed controllers will have sufficient sensitivity to detect a frequency deviation and initiate the release of active power to bring the frequency back to the permitted operating range of 49.5Hz to 50.5Hz by means of an integrated wind energy system or a battery energy storage system. Although maintaining the system frequency at 50 Hz is the ideal, real-world circumstances often make this unfeasible, hence a certain amount of variance is allowed.

RTDS is a simulation environment for industrial real-time power systems and controls that incorporates external hardware components. This aids in the analysis of its behavior during operations in real time. This chapter describes how the control schemes for the battery energy storage system and the wind energy system were created using RSCAD software and then applied to the network under investigation. The designed control scheme's principal purpose is to guarantee that the power system frequency stays within its operational range. The control schemes are designed in a way that during the times of high wind speed, the wind energy system serves as the primary source of active power reserves and assists in charging the battery energy storage system. In situations where the wind energy system is unable to supply the entire active power reserves—which can be caused by a variety of factors including a low wind speed, faults, interruptions for maintenance, etc.—the battery energy storage system will supply active power reserves.

It is simpler to evaluate the control scheme's behavior when it is fully integrated into the real-time power system when it is implemented on RTDS. To ensure that the control method is acceptable and effective for a real power system grid deployment, a variety of contingencies are used.

The format of this chapter is as follows. The wind energy system's modeling is the main topic of Section 5.2. The modeling of the battery energy storage system is covered in Section 5.3. The model and the active power control loop's architecture are shown in

Section 5.4. The simulation of several scenarios is described in Section 5.5 in order to examine the efficacy of the created active power control loop. The outcomes of the case studies that were simulated in this chapter are covered in Section 5.6. Finally, this chapter is concluded in Section 5.7.

5.2 Modelling of the Wind Power Plant

The 4.2 MW Vestas V117 wind turbine generators make up the wind power plant that is modeled in this section for the purpose of providing operating reserves. Every wind turbine in the wind farm powers a 4 MW squirrel-cage induction generator (SCIG), the specifications of which were taken from a book written by (Wu, et al., 2011).

The South African power company, Eskom, states that in order to ensure supply security during spikes in demand, it is imperative to keep a reserve margin over 15% when the demand for electricity rises. According to the selected IEEE 9 bus power system, the total load demand is 315MW. Next, the necessary operational reserve for the redesigned IEEE 9 bus power system can be computed using the formula below:

Operating Reserve = 15% x System load

= 0.15 x 315MW = 47.25MW

The simulated wind farm must have a maximum power output of 47.25 megawatts. When loaded, the wind turbine generator model produces about 3.68MW of output electricity. Consequently, the wind power plant will have 15 (3.68 MW) wind turbines in total, or 55.2 MW, with some additional electricity used to charge the battery energy system when wind speeds are high.

5.2.1 The RSCAD Wind Turbine Model

For an induction machine to behave as a generator of electricity, it requires a mechanical prime move to rotate its shaft so that it can produce electricity. The V117-4.2MW wind turbine from Vestas is the chosen prime mover for this project. The diagram below, Figure 5.1, shows the RSCAD model of the wind turbine.

For the wind turbine to start running and producing the mechanical power required by generator, it requires three inputs namely, the pitch angle (pitchdeg), wind speed in kilometers per hour (windkph), and the per unit speed (WTG1SPD). The wind turbine produces an output which is a per unit torque (WTG1TM), this torque is fed to the generator as input to drive the generator.

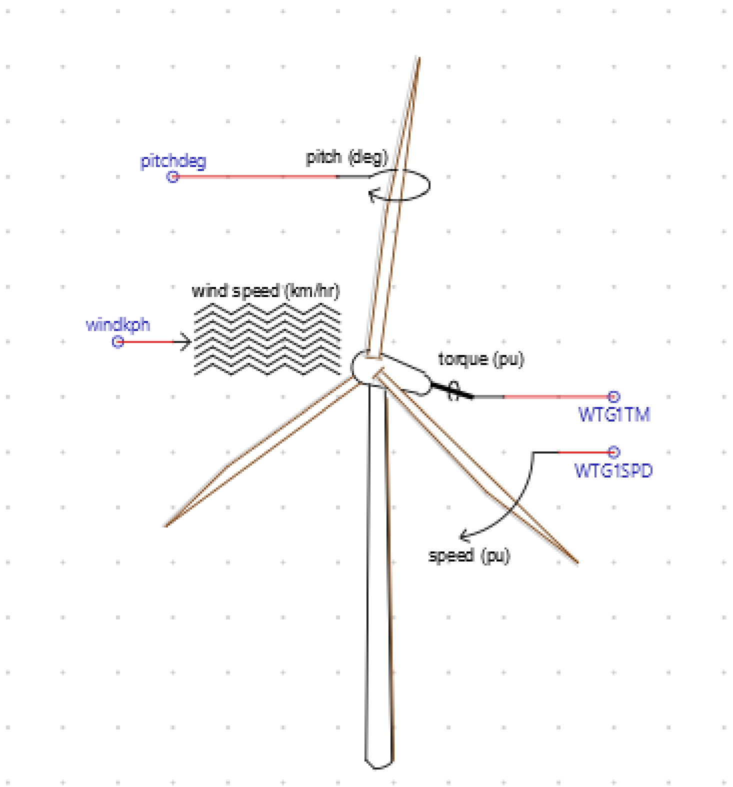


Figure 5.1: **The RSCAD wind turbine model**

5.2.1.1 Modelling of the Wind Turbine

According to the brochure for the V117- 4.2MW wind turbine as published by Vestas, the rotor diameter of this wind turbine is 117 m which means that the rotor radius as required by the model is 58.5 m.

Another turbine parameter that is required is the Gear Ratio which can be determined by looking at the amount of torque required by the machine, in comparison with the one produced by the turbine. The nominal numbers are used to compute a gearbox ratio. The induction generator's rated rotor speed is 1510.5 rpm, while the wind turbine's rotor rotates at 9.9 rpm at a nominal wind speed of 14 m/s (Wu, et al., 2011). The propeller, or turbine shaft, which is located on the secondary side of the gearbox in this instance, needs to rotate at least 1510.5 rpm in order for this generator to produce the rated power. Using the following expression, one can calculate the gearbox ratio:

$$G = \frac{\omega_{GR}}{\omega_{TR}} \tag{5.1}$$

The induction generator and wind turbine rotor nominal speed numbers are replaced as follows:

$$G = \frac{1510.5\ rpm}{9.9\ rpm}$$

$$G = \frac{50.35\pi\ rad/s}{1.036705\ rad/sec}$$

$$G = 152.5757576$$

An alternative approach to determining the gearbox ratio compares the torque generated by the turbine to the quantity needed by the machine. The wind turbine's mechanical torque expression can be written like this:

$$T_T = \frac{P_T}{\omega_{TR}} \tag{5.2}$$

$$T_T = \frac{4MW}{1.036705\ rad/sec}$$

$$T_T = 3.858378\ MN.m$$

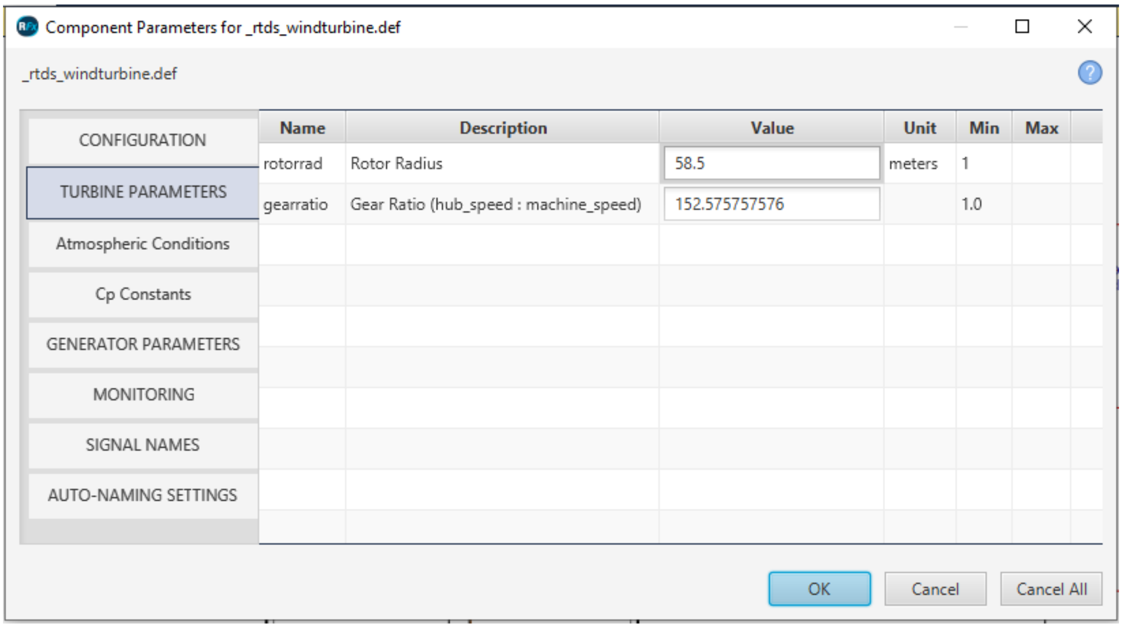
The mechanism outlined by the statement is used to transfer the mechanical torque needed to drive the wind turbine generator through the gearbox of the wind turbine,

$$T_G = \frac{T_T}{G} \tag{5.3}$$

Thus, the gear ratio can be computed using the formula below:

$$G = \frac{3.858378MN.m}{25.671kN.m}$$

$$G = 152.5757576$$



Name	Description	Value	Unit	Min	Max
rotorrad	Rotor Radius	58.5	meters	1	
gearratio	Gear Ratio (hub_speed : machine_speed)	152.575757576		1.0	

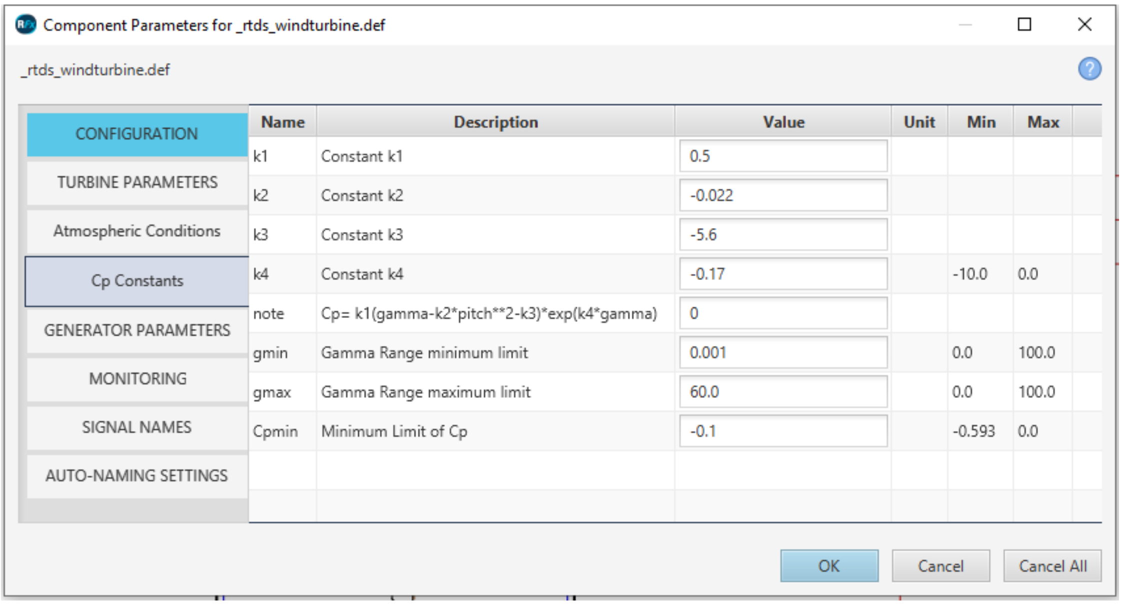
Figure 5.2: Modelling of the rotor radius and gear ratio as calculated above

Many equations can be used to calculate the power coefficient of the wind turbine. The RSCAD model requires four constants k_1, k_2, k_3 and $k_4$for it to compute the power coefficient which can be expressed as follows (Nomandela, et al., 2023),

$$C_p = k_1(\lambda + k_2\beta^2 + k_3)e^{k_4\lambda} \tag{5.4}$$

$$\lambda = \frac{v_w}{\omega_{TR}} \tag{5.5}$$

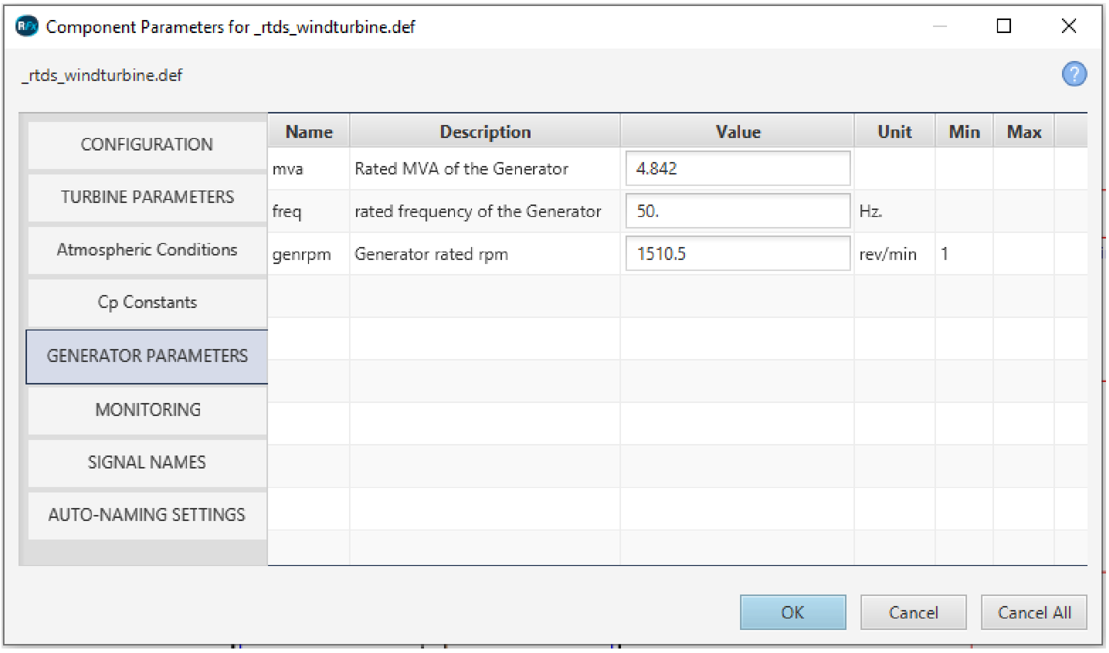
The constants used for the power coefficient formula are as follows, k_1= 0.5, k_2 = -0.022, k_3= -5.6 and k_4= -0.17.



Name	Description	Value	Unit	Min	Max
k1	Constant k1	0.5			
k2	Constant k2	-0.022			
k3	Constant k3	-5.6			
k4	Constant k4	-0.17		-10.0	0.0
note	Cp= k1(gamma-k2*pitch**2-k3)*exp(k4*gamma)	0			
gmin	Gamma Range minimum limit	0.001		0.0	100.0
gmax	Gamma Range maximum limit	60.0		0.0	100.0
Cpmin	Minimum Limit of Cp	-0.1		-0.593	0.0

Figure 5.3: Modelling of the constants required for the computation of the power coefficient

Information on the generator that the wind turbine will be driving is also needed for the RSCAD model of the wind turbine. The generator's rated MVA, frequency, and rated speed in rpm are the necessary parameters. These factors are displayed in Figure 5.4, the diagram below.



Name	Description	Value	Unit	Min	Max
mva	Rated MVA of the Generator	4.842			
freq	rated frequency of the Generator	50.	Hz.		
genrpm	Generator rated rpm	1510.5	rev/min	1	

Figure 5.4: Generator parameters as required by the wind turbine model

5.2.1.2 Wind Turbine Control logics

To acquire the appropriate output power from the wind turbine generator, two key variables that can be regulated are the wind speed and the pitch angle of the wind turbine. These two factors are controllable, as Figure 5.5, the diagram below, illustrates.

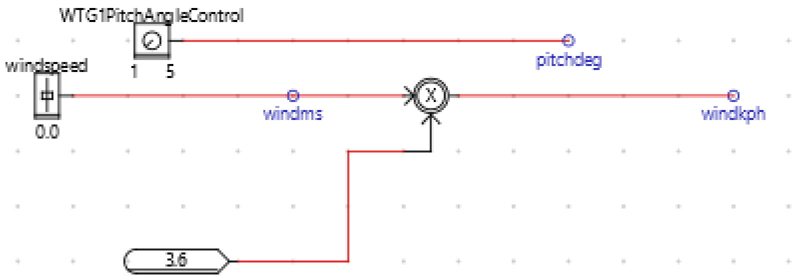


Figure 5.5: Control logic for Pitch Angle and Wind speed

The wind speed range or restrictions are stated in meters per second (m/s) on the datasheet for Vestas' V117-4.2MW wind turbine, and the wind speed input in kilometers per hour (km/h) was needed for the RSCAD wind turbine model. A control logic was created to convert the wind speed from meters per second to kilometers per hour since it is more practical to monitor and regulate the wind speed in meters per second.

The control logic is based on the following mathematical formula,

$$v_{kmh} = 3.6v_{ms} \tag{5.6}$$

The Vestas V117-4.2 MW wind turbine has an operating wind speed range of 3 m/s to 25 m/s. Additionally, the turbine rotor's rotational (angular) speed is set in accordance with the range of wind speeds; the data is displayed in Table 5.1 below.

Table 5.1: **The rotor's angular speed as well as the wind speed.**

Wind Speed (m/s)	The angular speed of the turbine rotor (rpm)	The angular speed of the turbine rotor (rad/sec)
3	2.1	0.219911
14	9.9	1.036705
25	17.6	1.843068

Turbine efficiency (Cp) is determined by two parameters: β and λ. Table 5.2 below displays the results of determining the Cp values for each tip speed ratio with varying pitch angle changes.

Table 5.2: **Cp values for various pitch angle modifications**

V_w	Cp	Wh	λ	β
3	0.405892	0.219911	13	0
14	0.375725	1.036705	13	5
25	0.285222	1.843068	13	10
36	-0.07679	2.666666	13	20
47	-0.82978	3.48	13	32

The value of the tip speed ratio (λ) is constant because the relationship between the increase in wind speed is directly proportional to the increase in the angular speed of the turbine rotor.

5.2.2 The RSCAD Induction Generator Model

As mentioned above, the wind turbine is used as a prime mover for the induction generator which means that it produces the mechanical power which is received by the generator as a per unit torque. Due to its affordability and ease of use, the squirrel-cage induction generator was chosen as the generator. The following diagram, Figure 5.6, shows the RSCAD model of an induction generator.

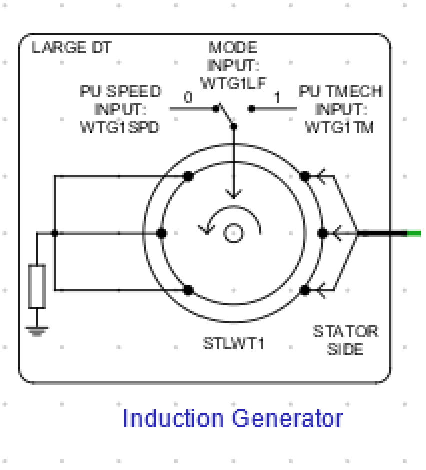
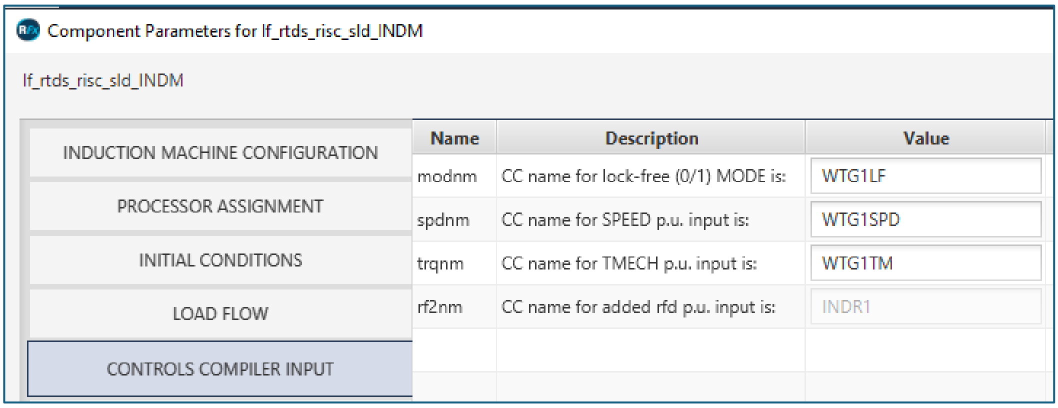


Figure 5.6: **RSCAD model of an induction generator (Type 2 WT)**

The wind turbine generator requires three inputs as shown in the diagram below, Figure 5.7. This first signal, WTG1LF, decides the mode of operation of the generator, and a switch is used to decide if the generator will be driven using per unit speed or per unit torque. The other two inputs, WTG1SPD and WTG1TM, are the per-unit speed and torque inputs which are used to rotate the shaft of the generator.



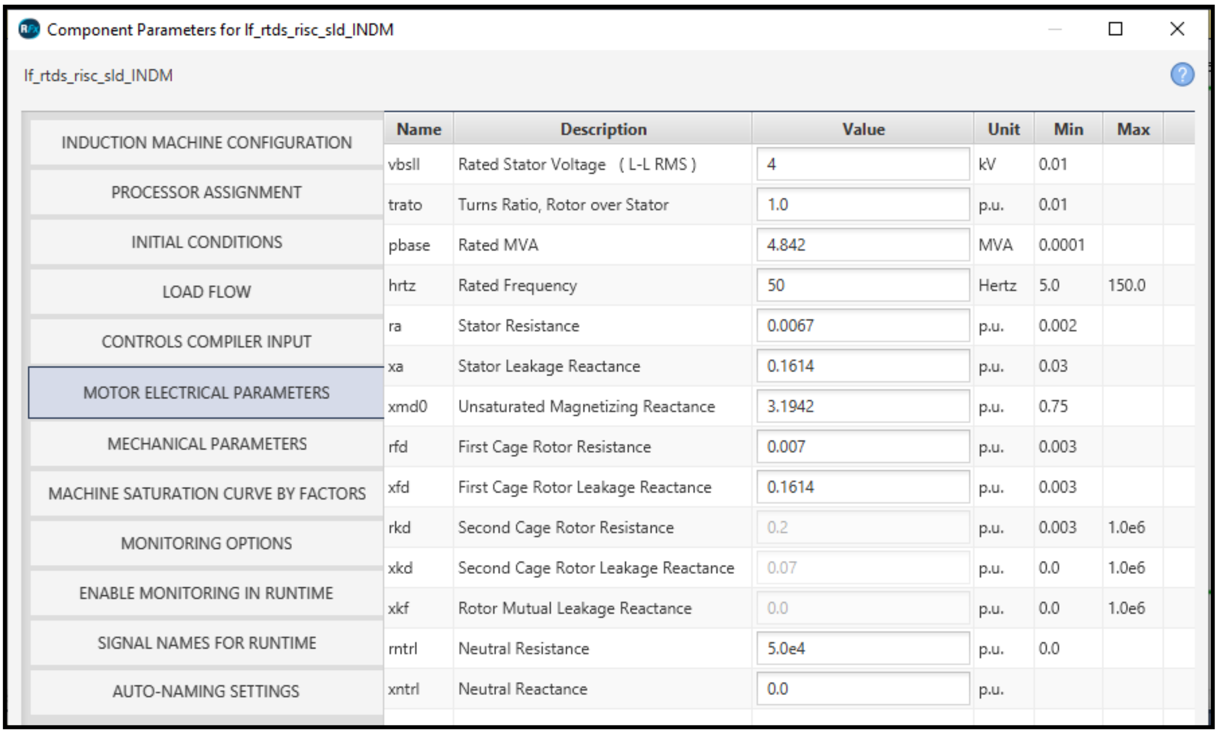
Component Parameters for lf_rtds_risc_sld_INDM

lf_rtds_risc_sld_INDM

Name	Description	Value
modnm	CC name for lock-free (0/1) MODE is:	WTG1LF
spdnm	CC name for SPEED p.u. input is:	WTG1SPD
trqnm	CC name for TMECH p.u. input is:	WTG1TM
rf2nm	CC name for added rfd p.u. input is:	INDR1

Figure 5.7: **Modelling of the inputs controlling the induction generator**

The electrical parameters of the induction generator are also required by the generator model. The diagram below, Figure 5.8, shows the electrical parameters used for this generator (Wu, et al., 2011). The electrical parameters below are for a 4MW squirrel cage induction generator.



Component Parameters for lf_rtds_risc_sld_INDM

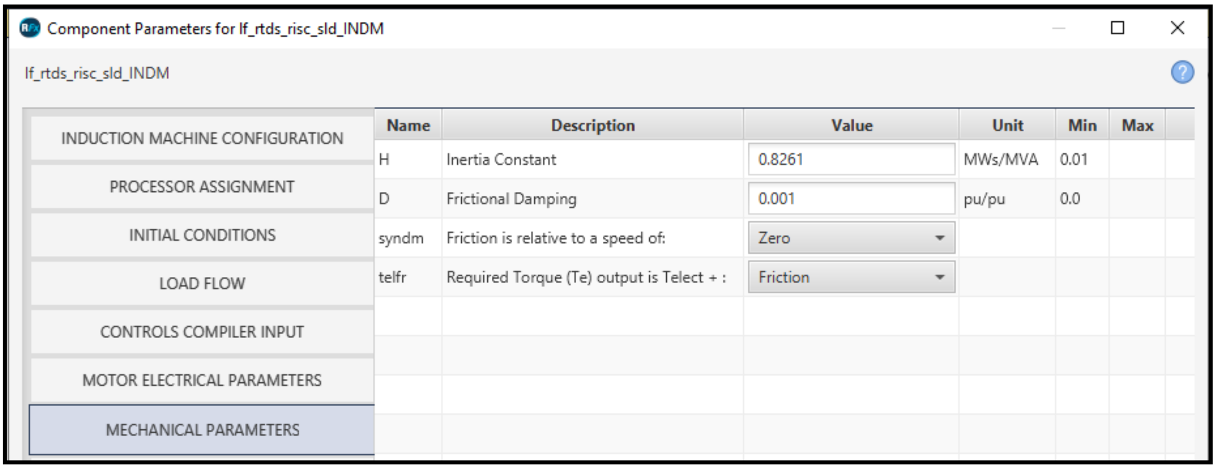
lf_rtds_risc_sld_INDM

- INDUCTION MACHINE CONFIGURATION
- PROCESSOR ASSIGNMENT
- INITIAL CONDITIONS
- LOAD FLOW
- CONTROLS COMPILER INPUT
- MOTOR ELECTRICAL PARAMETERS
- MECHANICAL PARAMETERS
- MACHINE SATURATION CURVE BY FACTORS
- MONITORING OPTIONS
- ENABLE MONITORING IN RUNTIME
- SIGNAL NAMES FOR RUNTIME
- AUTO-NAMING SETTINGS

Name	Description	Value	Unit	Min	Max
vbsll	Rated Stator Voltage (L-L RMS)	4	kV	0.01	
trato	Turns Ratio, Rotor over Stator	1.0	p.u.	0.01	
pbase	Rated MVA	4.842	MVA	0.0001	
hrtz	Rated Frequency	50	Hertz	5.0	150.0
ra	Stator Resistance	0.0067	p.u.	0.002	
xa	Stator Leakage Reactance	0.1614	p.u.	0.03	
xmd0	Unsaturated Magnetizing Reactance	3.1942	p.u.	0.75	
rfd	First Cage Rotor Resistance	0.007	p.u.	0.003	
xfd	First Cage Rotor Leakage Reactance	0.1614	p.u.	0.003	
rkd	Second Cage Rotor Resistance	0.2	p.u.	0.003	1.0e6
xkd	Second Cage Rotor Leakage Reactance	0.07	p.u.	0.0	1.0e6
xkf	Rotor Mutual Leakage Reactance	0.0	p.u.	0.0	1.0e6
rntrl	Neutral Resistance	5.0e4	p.u.	0.0	
xntrl	Neutral Reactance	0.0	p.u.		

Figure 5.8: **Modelling of the electrical parameters of the induction generator (Wu, et al., 2011).**

One additional configuration is the inertia constant of the generator. According to (Wu, et al., 2011), this generator has a 4 MW rated output and a 4.842 MVA rated apparent power. The generator specifications' values are used to determine MWs/MVA, as indicated by its units. This number is then placed in the mechanical parameters, as seen in Figure 5.9 of the induction generator parameter settings below.



Component Parameters for lf_rtds_risc_sld_INDM

lf_rtds_risc_sld_INDM

- INDUCTION MACHINE CONFIGURATION
- PROCESSOR ASSIGNMENT
- INITIAL CONDITIONS
- LOAD FLOW
- CONTROLS COMPILER INPUT
- MOTOR ELECTRICAL PARAMETERS
- MECHANICAL PARAMETERS

Name	Description	Value	Unit	Min	Max
H	Inertia Constant	0.8261	MWs/MVA	0.01	
D	Frictional Damping	0.001	pu/pu	0.0	
syndm	Friction is relative to a speed of:	Zero			
telfr	Required Torque (Te) output is Telect + :	Friction			

Figure 5.9: **Modelling of the mechanical parameters of the generator**

The mechanical power input is converted to electric power via the induction generator's shaft. Not even the torque from the prime mover will cause the voltage at the generator's stator terminal to rise. An exciting circuit is needed to cause a voltage build-up on the induction generator's stator terminals. In order to generate voltage from the little current available at the stator terminals while the machine's rotor rotates, extra circuitry is needed. As a result, the excitation circuit is created in the section below, and the induction generator's electrical properties are used to compute the circuit's parameters.

5.2.2.1 Generator excitation modelling

For an induction generator to start producing electricity when it is driven by a prime mover, a certain amount of capacitance needs to be connected to the stator side of the generator to excite the machine. Self-excitation of induction machines occurs when the capacitive reactive current flowing in the excitation capacitors is greater than the magnetizing current of the induction machine. To create self-excitation, the capacitive reactance of the excitation capacitor bank must be less than that of the induction machine magnetizing inductance.

The induction machine magnetizing reactance can be calculated as follows,

$$X_m = 2\pi f L_m \tag{5.7}$$

$$X_m = 2\pi.(50).(0.033597)$$

$$X_m = 10.5548\Omega$$

where X_m is the magnetizing reactance of the induction machine, f is the system frequency and L_m is the magnetizing inductance of the induction machine used in this project. The magnetizing inductance is documented in (Wu, et al., 2011) as part of the specifications for a 4MW squirrel-cage induction generator.

Therefore, for a three-phase excitation capacitor bank, the capacitive reactance needs to be less than 3 times the value of the magnetizing reactance calculated above as shown in the calculation below,

$$X_C < 3.X_m \tag{5.8}$$

$$X_C < 3.(10.5548)$$

$$X_C < 31.664\Omega$$

The statement "$X_C < 3.X_m$" is a widely accepted rule of thumb in the field of electrical engineering, and it can be found in various textbooks and publications including (IEEE Std 18, 2017) and (Fitzgerald & Umans, 2013).

Therefore, the capacitance required to excite the induction generator can be calculated as follows,

$$C_{EXC} > \frac{1}{2\pi f X_C} \tag{5.9}$$

$$C_{EXC} > \frac{1}{2\pi.(50).(31.664)}$$

$$C_{EXC} > 100.526\mu F$$

The following diagram, Figure 5.10, shows the modelled capacitor bank for the excitation of the induction generator. There is a total of 10 delta-connected capacitors connected in parallel with each having a capacitance equal to 13.5 µF. For excitation, only 8 units are needed, where each capacitor would need to have a capacitance of above 12.57 µF (100.5 µF divided by 8). The value of 13.5 µF per capacitor was chosen to achieve the rated stator voltage. A control logic was designed to add or remove one capacitor by closing or opening the breaker of a certain number of capacitors until the power factor is within acceptable limits which is between 0.95 and 1.05. The user also has the benefit of manually switching on or off one capacitor at a time to achieve excitation. Once excitation has been achieved, the user can manually switch off the capacitors one by one until the voltage is within acceptable range for integration to the grid. If the voltage is too low or too high, the breaker for integrating into the grid will refuse to close.

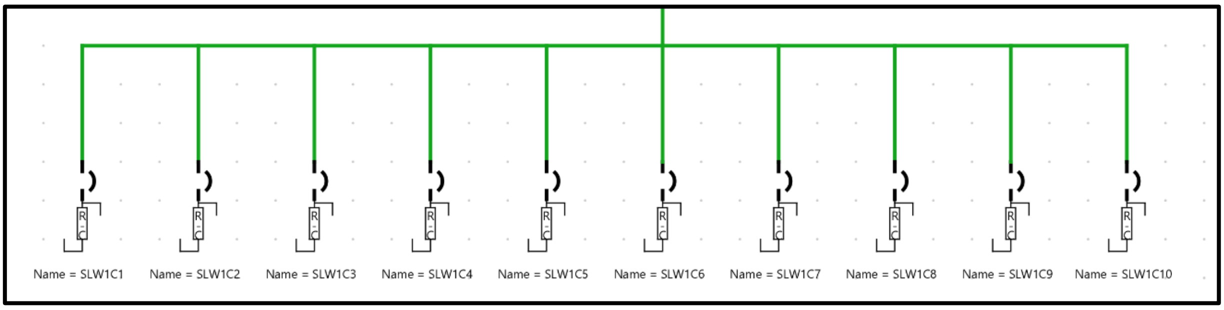


Figure 5.10: **Induction machine excitation capacitor bank**

The diagram below, Figure 5.11, shows the complete wind energy system as modelled on the RSCAD simulation program. A scaled transformer has been used instead of a normal power transformer to multiply the output of one wind turbine so that it can result in the desired output power. The motivation behind this is because of the simulation package constraints, the hardware that is present at the substation automation laboratory at Cape Peninsula University of Technology can only handle a certain number of nodes due limited number of RTDS processor cards. Modelling all 15 required wind turbine generators was going to cause issues with the real-time simulation of the power system network.

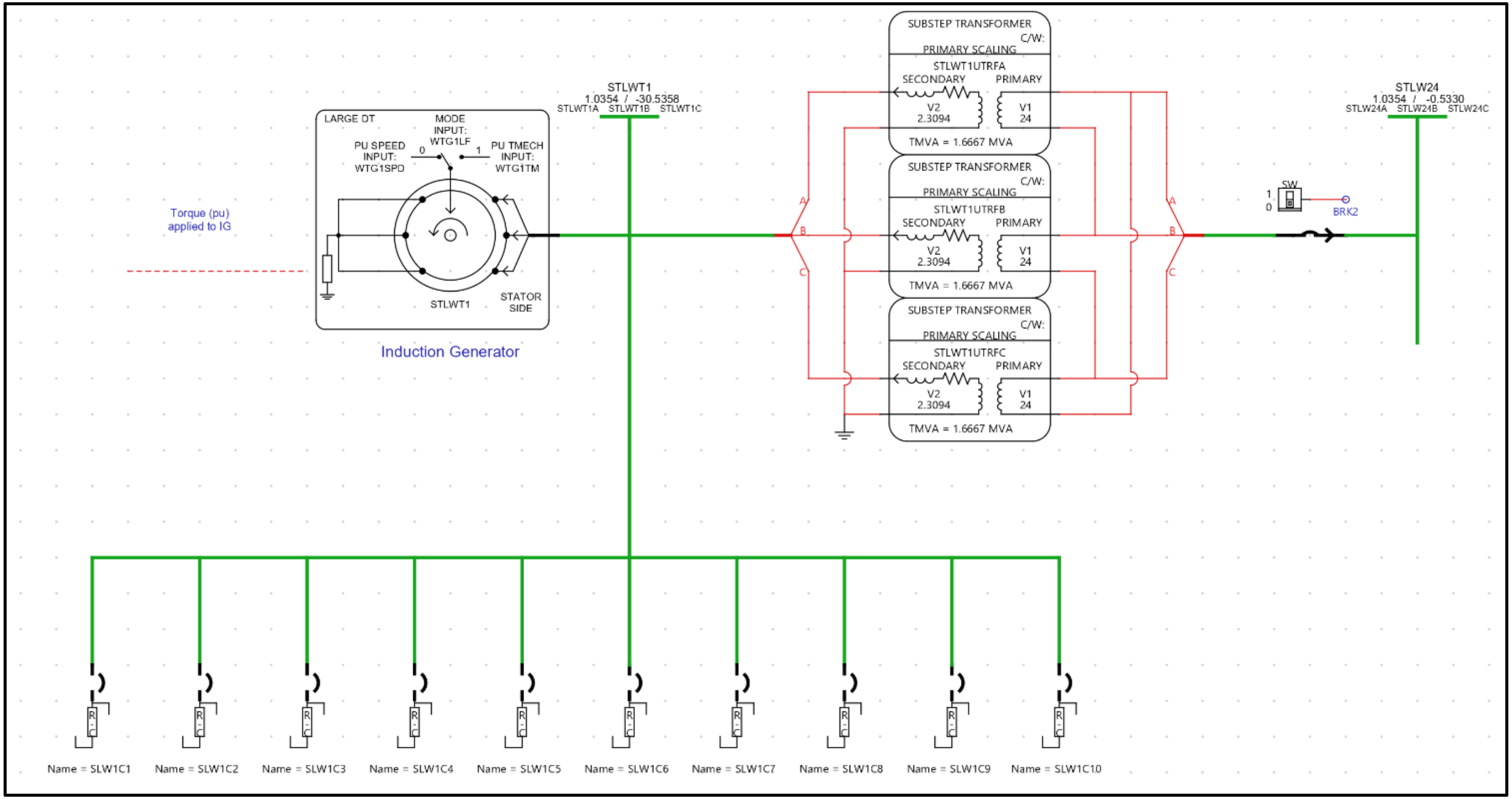


Figure 5.11: Complete wind energy system

5.3 Modelling of the battery energy storage system

The intermittent nature of wind energy is well-known. Because wind energy systems have variable output, there's a chance that it won't always be enough to offer the necessary operating reserves at any given moment. Because of this, a battery energy system needs to be modeled in a way that allows it to store energy during times of high wind and release it when operating reserves are needed and the wind energy system is unable to supply the necessary quantity.

The diagram below, Figure 5.12, shows the battery energy storage system using the average value model (AVM) as modelled on the RSCAD software package. The BESS consists of battery banks, an inverter for converting a DC voltage to an AC voltage of 0.48kV, and a transformer for stepping up the 0.48kV from the inverter to 24kV. The BESS modelled below is rated for 3MVA. An AVM is used to represent the DC voltage that the batteries provide to the converter. Next, the transformer is connected to the converter's AC side.

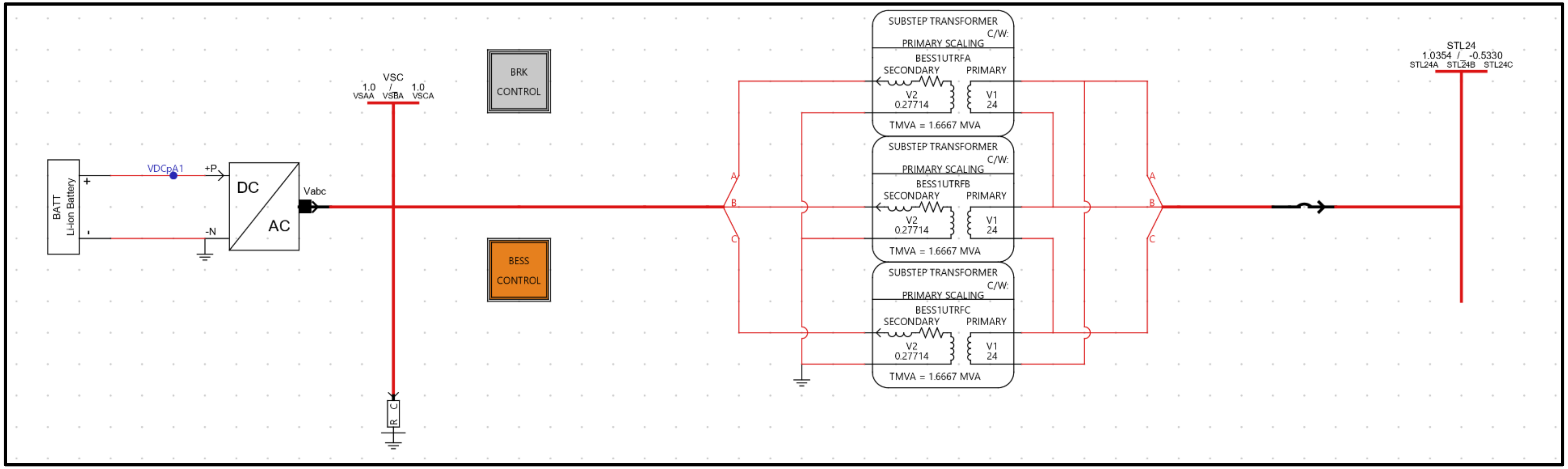


Figure 5.12: Battery Energy Storage System using AVM

Grid-connected mode and island mode are the two control modes available for the BESS system. The only differences between the two modes of operation are in the outer loop controls, while the inner current control loop remains the same. An outside voltage control loop is used for islanded mode and an outer real/reactive power control loop is used for grid-connected mode. In addition, a voltage-controlled oscillator (VCO) is utilized in islanded mode to generate the necessary phase information for the controls, whereas a phase locked loop (PLL) is used in grid-connected mode.

5.4 The modelling and integration of the WES and BESS active power compensator

In order to increase the system frequency and offset the active power gap between the load demand and the rated power output of the synchronous generators (grid), the wind energy system and the battery energy storage system were incorporated into the grid. When a load demand contingency was applied in the above section 5.2 by increasing the load by 15% in 15 steps, the frequency dropped to a value of 49.49Hz in the end and it stayed constant at that value. The 15% load increase means that the total load of 315 MW would increase by 47.25 MW to a value of 362.25 MW. A further contingency in the grid can have a severe impact if the frequency is not corrected and is left at 49.59Hz which is still within the acceptable limits of 49.5Hz to 50.5Hz. In order to bring the system frequency closer to the nominal frequency of 50 Hz, the wind energy system and the battery energy storage system are integrated.

To use the wind energy system and the battery energy storage system as the active power compensator when the frequency is deteriorating, an active power control loop to release active power based on the system frequency deviation is required. The wind energy system and the battery energy storage system will be integrated into the grid but not supply any power to the grid; therefore, its output power is set to a minimum (approximately zero) at a steady state.

5.4.1 WES and BESS active power supplementary control loop

The system frequency increases (from 50Hz) when the load demand is less than the available generation capacity and decreases when the load demand is greater than the available generation capacity. When the load demand is equal to the available generation capacity, the frequency stays at 50Hz. When the load increases, the synchronous generators try to supply the load demanded which may be more than what they can provide. The developed control system must ensure that the synchronous generators do not go above their capacity. When the load demand goes beyond the capacity of the synchronous generators, the wind energy system must be switched on to supply the difference. When the wind energy system is unable to supply the required active power or can only supply a portion of it, a battery energy storage system must take over and supply the other portion or the total required active power should the wind energy system not be able to provide active power at all.

The diagram below, Figure 5.13, shows the flow chart of the developed active power control algorithm. The operates as follows:

- Compares the measured system frequency with a set reference of 50 Hz.
- If the measure frequency is equal to the set reference, this means that there is no need for both the WES and BESS to export active power to the grid. The WES charges the BESS with the available output power.
- If the measured frequency is less than the set reference frequency, this means that the demand is greater than the supply and this needs to be corrected. The required active power to balance the demand and supply is then calculated.
- The algorithm compares the required active power with the power output of the WES which can depend on many things including the wind speed and turbine outages.
- If the output power of the WES is greater or equal to the required active power, the WES exports the required active power to the grid and charges the BESS with the excess power.
- If the output power of the WES is less than the active power required, the BESS supply’s the difference or the total required active power if the WES is completely out.
- This algorithm is continuous and automated.

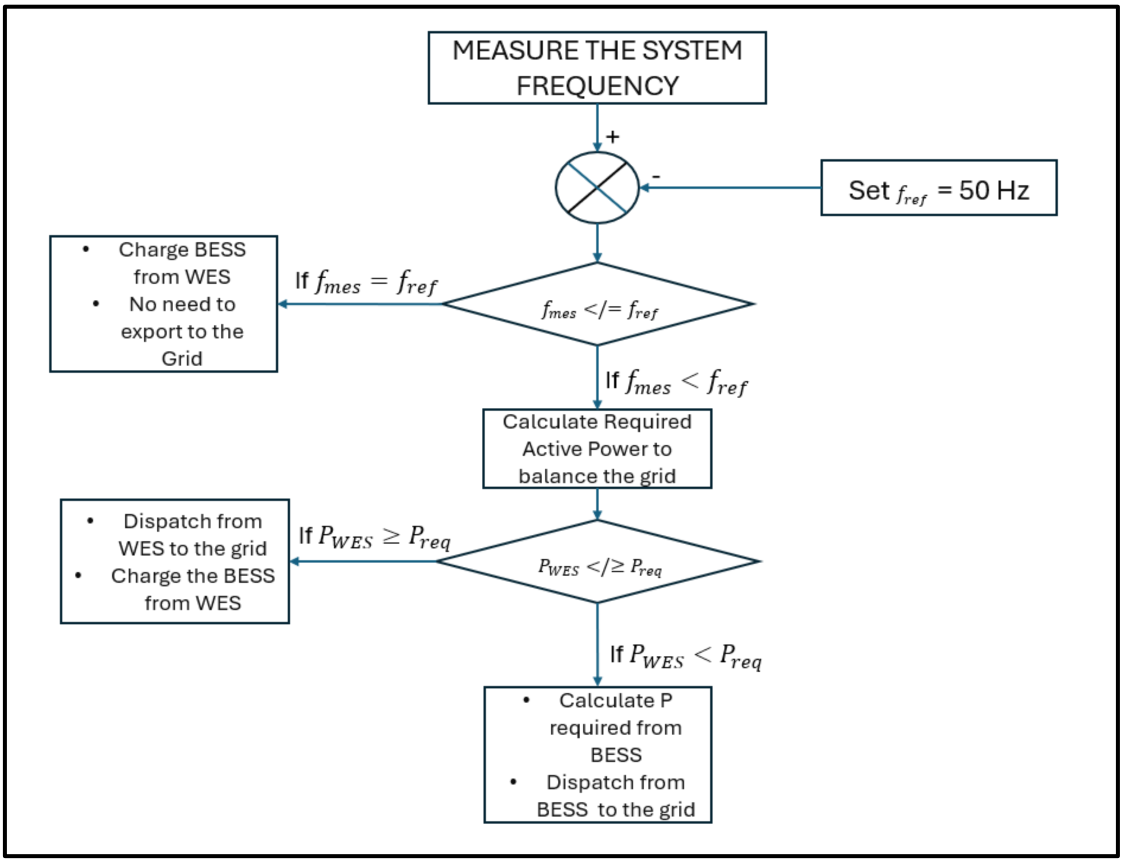


Figure 5.13: Flow chart of the active power control algorithm

Initially, the system frequency and total power generated were found to be related. With the aid of an RTDs simulation program, this was accomplished practically. The influence on frequency was seen as the load was increased in steps of 5 MW, resulting in an increase in total power output in stages of 5 MW. The practical experiment's outcomes are displayed in Table 5.3 below.

Table 5.3: Practical experiment results showing the relationship between the total power generated and the system frequency

Total Power Generated (MW)	System Frequency Measured (Hz)
320.1	50
325	49.95
330	49.92
335	49.87
340	49.83
345	49.79
350	49.75
355	49.7
360.1	49.66
365.1	49.62

370.1	49.58

Creating a mathematical equation based on experimental data is normal and appropriate. "Data-driven modeling" or "empirical modelling" are terms used to describe this procedure. You can build a potent tool for understanding complicated events, optimizing systems, and forecasting future behavior by formulating a mathematical equation based on experimental data. The outcomes of experiments can be utilized to:

- Identify patterns and relationships between variables
- Develop a mathematical model that describes the behaviour of a system
- Validate the model by comparing it with additional experimental data

The link between total power generated and system frequency is represented graphically in Figure 5.14, which is the diagram below. A linear function was created using the MS Excel plot (Figure 5.14) to determine the frequency at various total power generated values.

The formula that can be used to find the system frequency of this specific model at a given total power generated value is as follows:

$$f = -0.0084P_{Load\ demand} + 52.644 \tag{5.10}$$

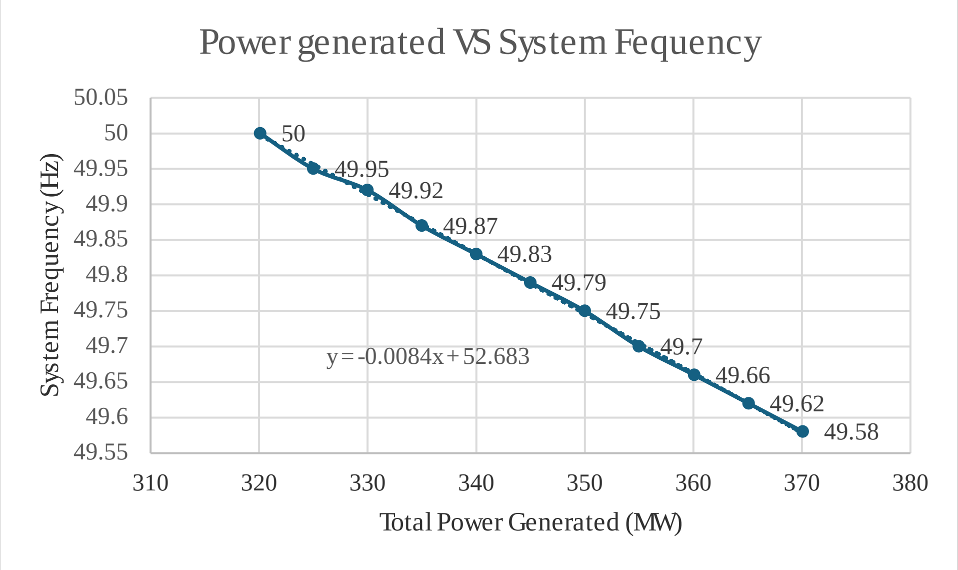


Figure 5.14: **Graphical representation of the relationship between the total power generated and the system frequency**

The wind energy system is modeled as the primary source of active electricity to maintain supply and demand equilibrium. Owing to the well-known intermittent nature of wind energy, it is also necessary to model a battery energy system to supply the necessary active power in situations where the wind energy system is unable to do so. There are a number of reasons why the wind energy system might not be able to supply the necessary active power, such as low wind speed intervals, wind turbine malfunctions, and planned maintenance downtime.

To determine the precise power differential between the total power produced by the synchronous generators and the load demand, the equation 5.10 above is adjusted. The following formula can be used to determine how much active power will be needed from the battery energy system and wind energy system to stabilize the frequency at 50 Hz:

$$P_{required} = \frac{52.644 - f_{measured}}{0.0084} - P_{Load(steady\ state)} \tag{5.11}$$

Where $P_{required}$ is the required active power that must be generated by the wind energy system and/or battery energy storage system to stabilize the system frequency at 50Hz, $f_{measured}$ is the measured frequency which varies depending on the load demand, $P_{Load(steady\ state)}$ is the load demand at a steady state.

Figure 5.15 below shows the developed logic in RSCAD (from equation 5.11) to calculate the active power required from the wind energy system and/or battery energy storage system to stabilize the frequency at 50Hz. This logic uses the measured frequency to calculate the power generated by all synchronous generators. The aim is not to operate the generators above their rated active power value. The logic then calculates the active power required to keep the generators operating at their rated limits.

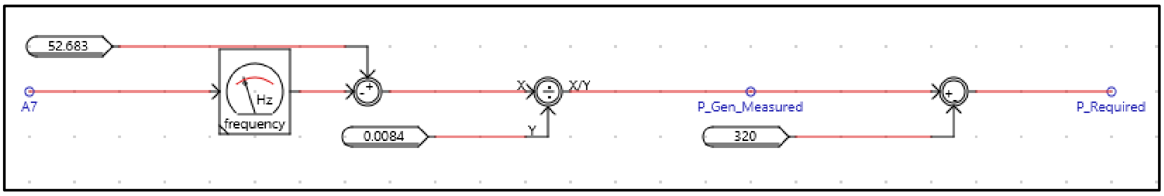


Figure 5.15: Total active power required to stabilize the system frequency at 50Hz

Once the required active power to stabilize the system frequency at 50Hz has been established. A scaling component that will decide the output power of the wind energy system based on the frequency deviation must be calculated. The calling components amplified the output of the wind turbine generator as there was only one wind turbine modelled due to the constraints with the processor of the simulation package. The mathematical modelling of the wind turbine generator active power compensator scaling is given in equation 5.11 below.

$$Scale_{WES} = \frac{P_{Load-measured}+P_{BESS-charging}-P_{Load(steady\,state)}}{P_{WTG1}} \tag{5.12}$$

Where $Scale_{WES}$ is the signal that is going to be sent to the wind energy system to decide the power output, $P_{Load-measured}$ is the measured total power demanded, $P_{BESS-charging}$ is the amount of power that is dedicated to charging the battery energy system during periods of high wind speed and is set as a constant of 3MW, $P_{Load(steady\,state)}$ is the total load demanded at steady state is a known value of 315MW, and lastly P_{WTG1} is the measured output power of the wind turbine generator that has been modelled.

In the diagram below, Figure 5.16, the logic developed in RSCAD to calculate the scaling component which is sent as a signal to the wind energy system to decide the power output of the wind power plant. When a contingency is applied by increasing the steady-state load demand of 315MW by 15%, the active power required becomes 47.25MW. Therefore, the modelled wind energy system is expected to be able to provide the required 47.25MW of active power. When integrated into the grid, one wind turbine generator produces roughly 3.68MW of power, which means that 15 wind turbine generators are needed to produce the 55.2MW of power which would be able to stabilize the system frequency and charge the battery energy storage system during periods of high wind speed. Hence the scaling component is limited to a maximum value of 15. This logic calculates the ratio of the required active power to the output power of the WES. The ratio is used to multiply the output of the modelled WT (3.68 MW) and the total power is exported to the grid.

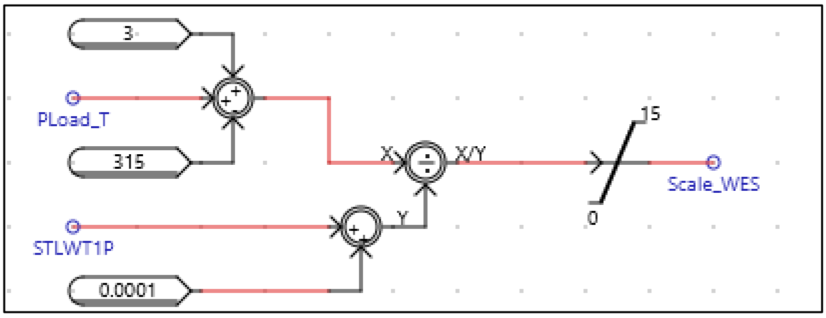


Figure 5.16: **Wind power plant active power scaling control**

Due to many reasons including the intermittency nature of the wind resource, unforeseen wind turbine or wind turbine generator faults, or scheduled maintenance outages, the wind energy system might not be able to provide the exact total active power required by the grid to restore the frequency to 50Hz. In order for the energy storage system to assist with active power correction in the event that the wind energy system is inefficient, the control scheme for the battery energy storage system must be created. It is crucial to remember that while the battery energy storage system can export active power to the grid, it also requires the import of active power in order to be charged. Because of the configuration of this type, the battery energy storage system can only be charged by the wind energy system and not by the grid itself.

When the wind energy system is unable to stabilize the frequency at 50 Hz, each battery bank must release a certain amount of active power, which may be calculated using the following mathematical equation.

$$PREF_{BESS} = \frac{P_{Load-measured} - P_{Load(steady\,state)} - P_{WES-total} + P_{required}}{Scale_{BESS}} \tag{5.13}$$

Where $PREF_{BESS}$ is the signal that is sent to the battery energy storage system as a reference that determines how much active power should each battery bank produce to stabilize the frequency if the are 10 different battery banks that can provide 4.72MW each. This signal has two possible states: positive indicates that the system is exporting and discharging to the grid, and negative indicates that it is importing and charging from the wind energy system. $P_{WES-total}$ is the total active power produced by the wind energy system. $Scale_{BESS}$ is the number of battery banks that make up the battery energy storage system.

Figure 5.17, the diagram below, illustrates the control logic that was created in RSCAD to scale the battery energy storage system and supply the necessary active power to maintain the power system's frequency at 50 Hz. This reasoning contrasts the WES's output power with the active power needed to maintain supply and demand balance. In the event that the grid's necessary active power is greater than the output power of the WES, the logic determines the amount of active power that the BESS must provide and transmits the result to the BESS scaling, which increases the value to a large-scale.

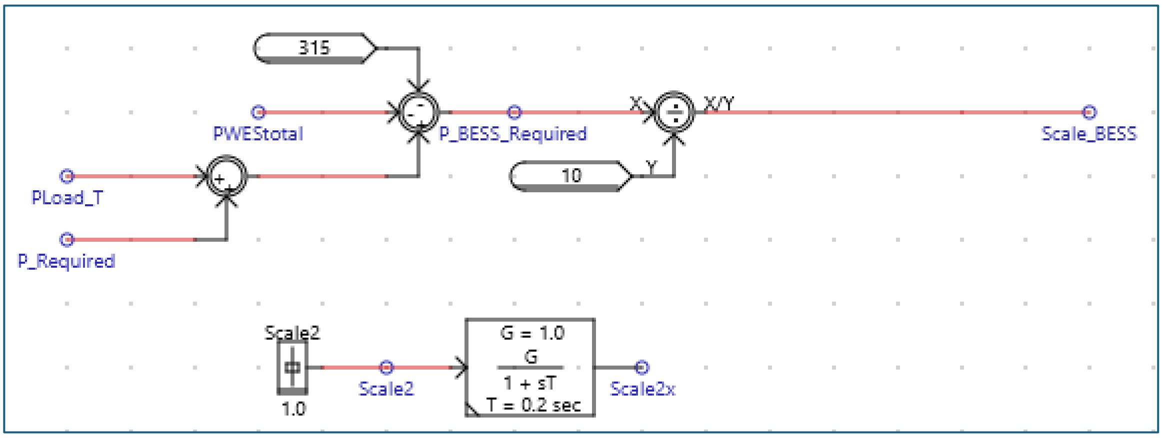


Figure 5.17: Battery energy storage system active power scaling control

5.5 Integration of the WES and BESS into the modified IEEE 9 bus system

Real-Time Digital Simulator (RTDS) and the commercial software platform RSCAD work together in real time. The power system network was developed using the RSCAD draft of RTDS. The aim of developing this network was to evaluate the effect of grid contingencies like load demand increase and generator unit loss on system frequency and voltage. For this purpose, an IEEE 9 bus benchmark system as provided on the RSCAD software package was modified slightly. The network consists of three synchronous generators which contain internal voltage step-up transformers, 3 dynamic loads, and 6 transmission lines. The network has been modified to operate at a frequency of 50Hz which is a standard in the South African power system.

The diagram below, Figure 5.18, shows the complete RSCAD or RTDS model that has been built for this project. The model consists of a wind energy system and a battery energy storage system integrated into the modified IEEE 9 bus power system. The grid is responsible for providing the nominal system load. In case there is a sudden imbalance on the grid, which may be caused by ab increase in load demand or a loss of a generator, the wind energy system and the battery energy storage system have to take over and supply the required operating reserves. Shown on the diagram below, is a simplified draft of the project, and the control logic and calculation blocks can be found inside the hierarchy boxes in the diagram.

The network diagram shown in Figure 5.19 was developed using the RSCAD runtime of RTDS. The runtime diagram gives the user the privilege to control and vary some network components in real-time. The runtime diagram is designed in such a way that it represents exactly what is developed in the RSCAD draft. This is to help operators who were not involved in the design of this network to be able to understand all the signals and be able to operate the network simulation.

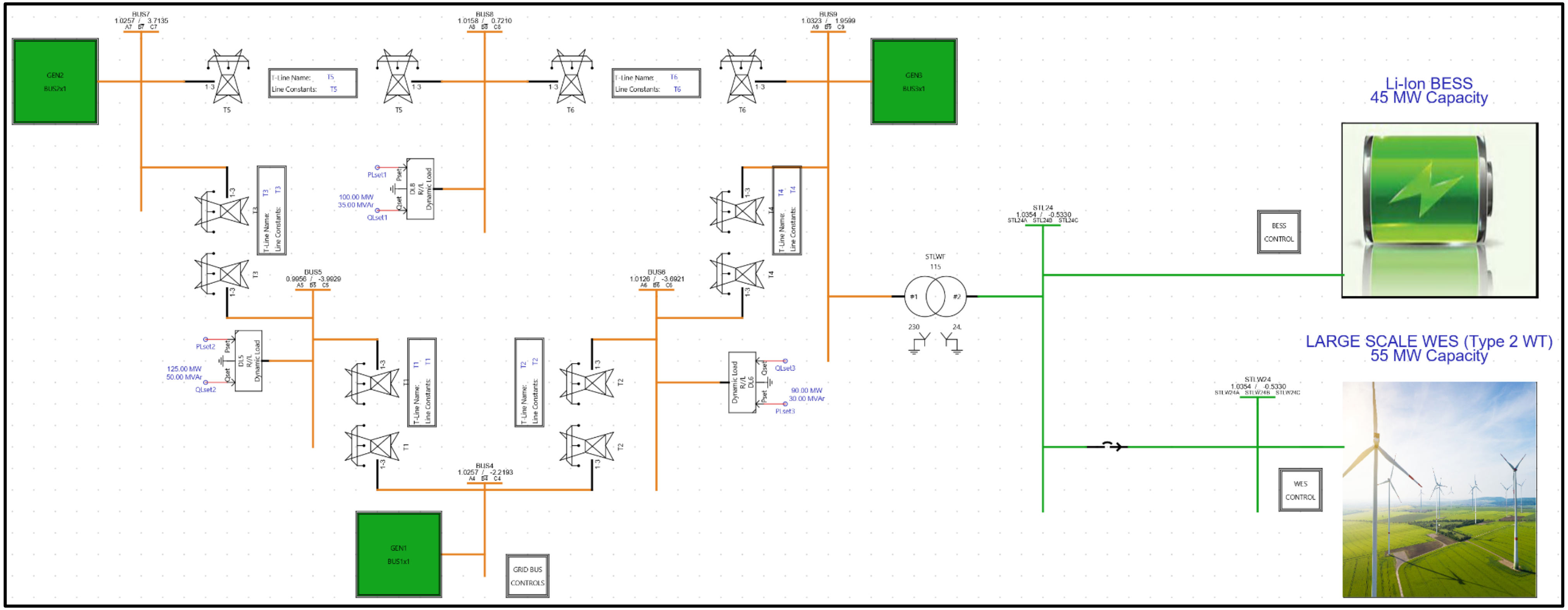


Figure 5.18: Modified IEEE 9 bus system and integration of WES and BESS into the model

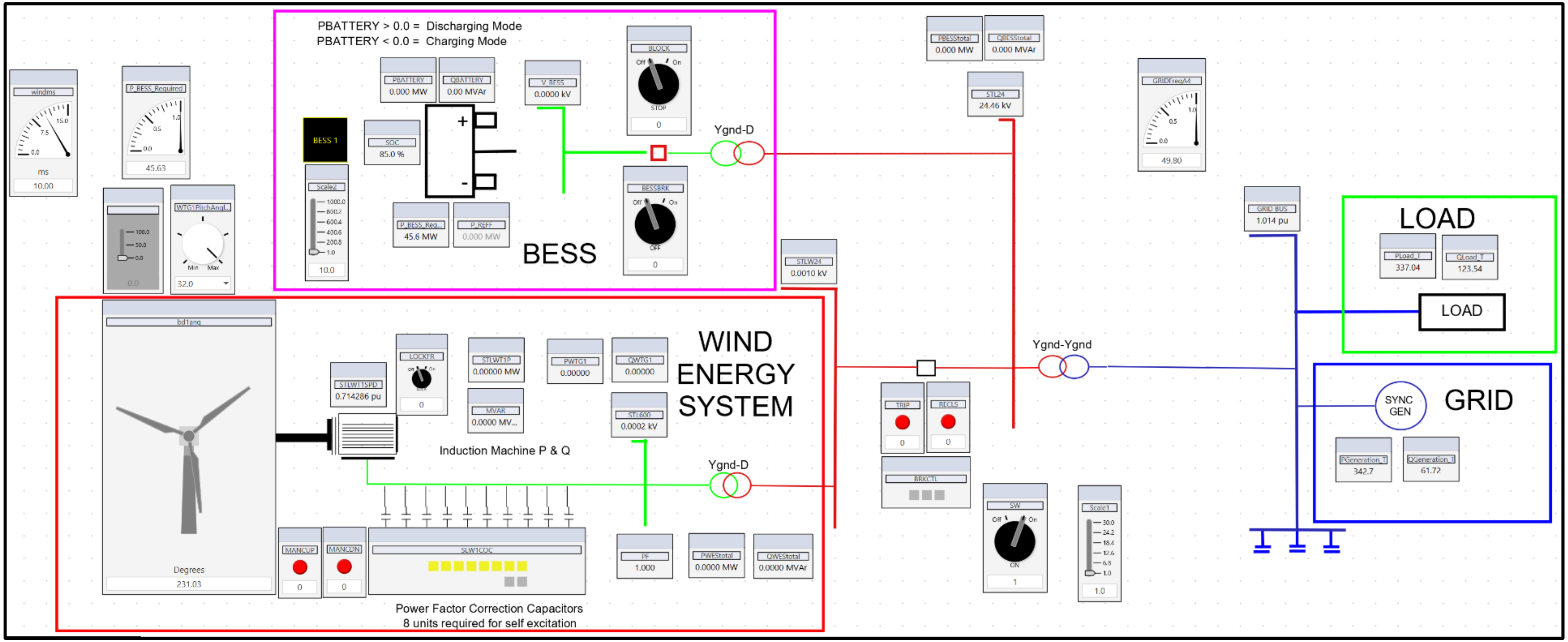
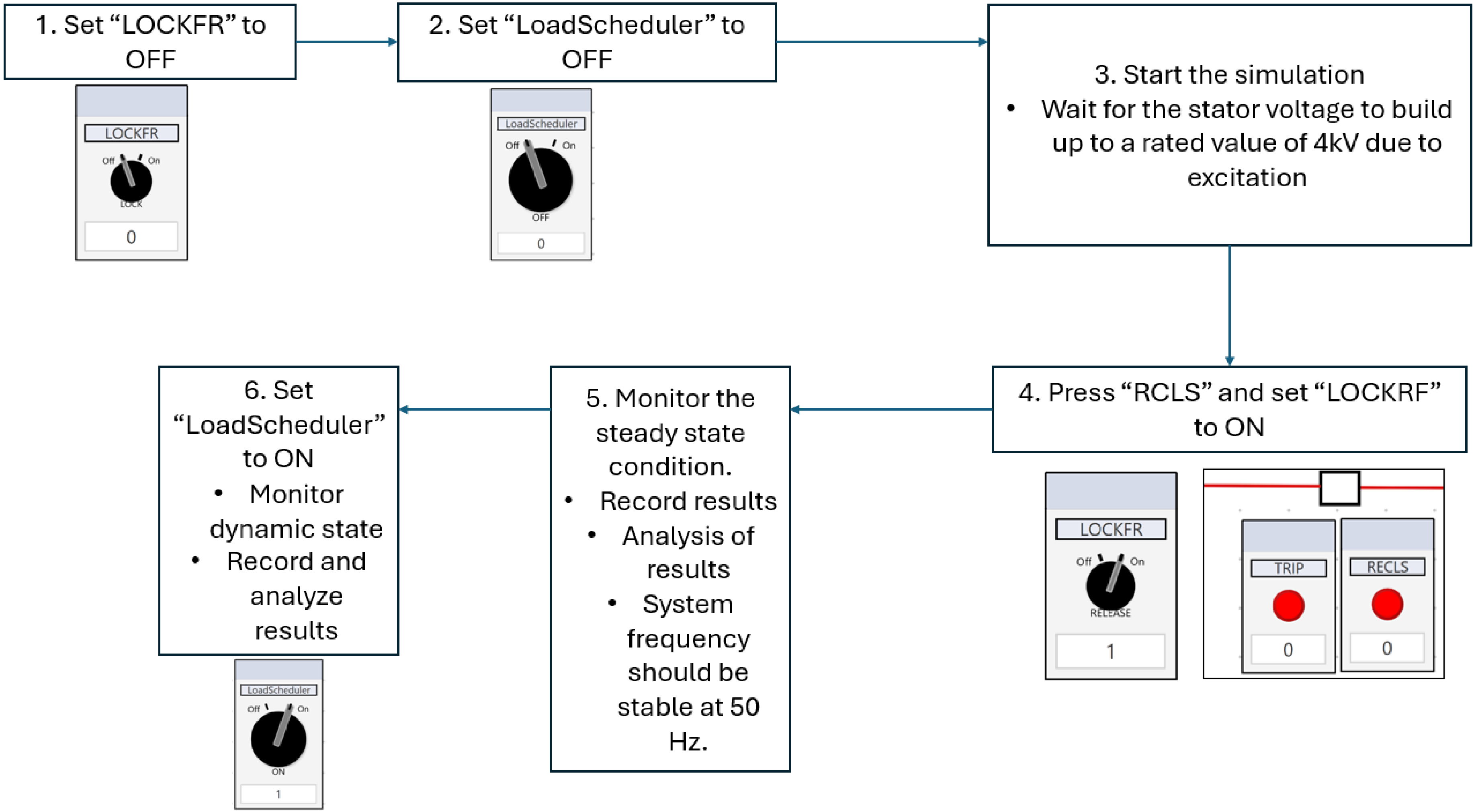


Figure 5.19: RSCAD runtime diagram for the integrated WES and BESS



1. Set "LOCKFR" to OFF

2. Set "LoadScheduler" to OFF

3. Start the simulation

- Wait for the stator voltage to build up to a rated value of 4kV due to excitation

4. Press "RCLS" and set "LOCKRF" to ON

5. Monitor the steady state condition.

- Record results
- Analysis of results
- System frequency should be stable at 50 Hz.

6. Set "LoadScheduler" to ON

- Monitor dynamic state
- Record and analyze results

Figure 5.20: Procedure to start the simulation on RTDS runtime

The following procedure can be followed to start the system as depicted in Figure 5.20:

(1) Set “LOCKFR” to OFF.

The LOCKFR switch is used to decide the mode of operation(input) for the induction generator which can be the per-unit speed or the per-unit mechanical torque of the prime mover.

(2) Set “LoadScheduler” to OFF.

LoadScheduler is an ON/OFF switch that is used to simulate a load increase contingency. At the beginning of the simulation, this variable needs to be OFF so that the steady state condition can be monitored and analyzed.

(3) Start the simulation case and wait for the voltage to build up to 4kV on the stator terminals of the induction machine.

This is due to the excitation capacitors which are switched on automatically as a controlled logic has been built for that purpose. According to the calculations, a total of 8 units are required for self-excitation of the machine. The other two units will aid in power factor correction. Once the voltage reaches 4kV on the stator terminals, follow step 4.

(4) Press “RCLS” and set “LOCKFR” to ON.

The RCLS push button is used to close the breaker that integrates the wind energy system to the grid. A synchronism check logic has been modelled, the logic compares the voltage coming from the wind energy system with the voltage on the grid and if these two do not match, the breaker will not close. This is to ensure that the wind energy system is supplying voltages that are within acceptable limits to the grid. LOCKFR allows the wind farm to send rated power to the grid. Under nominal conditions, the output power of the wind energy system will be just 3.68MW and will be used for charging the battery energy storage system.

(5) Monitor steady state condition.

(6) Switch LoadScheduler ON to simulate a load increase contingency and analyze the dynamic condition.

It is important to also note the following:

$$PREF < 0 \ = Discharging\ mode$$

$$PREF > 0 \ = Charging\ mode$$

The charging or discharging mode of the battery energy storage system is determined by the grid requirements and the availability of the wind energy resource. The BESS will discharge to the grid when the wind energy system is not supplying enough active power to the grid and the BESS will operate in charging mode when the wind energy system is generating enough active power.

5.5.1 The application of contingencies to validate the effectiveness of the developed control scheme

This section examines the efficacy of the suggested control strategies in preserving grid stability by keeping the system frequency at 50 Hz using a load growth contingency. In Chapter 4 above, it was shown that when a 15% load increase contingency is applied to the network, the frequency drops to 49.59Hz. This value is still within the acceptable limits which are between 49.5Hz and 50.5Hz but it would be unsafe to operate the grid at that value as further disturbances can lead to severe consequences.

Active power control loops for the wind and battery energy storage systems were created in the previous section of this chapter so that both systems could participate in active power compensation. Subject to the availability of wind resources, the control system is configured so that the wind energy system serves as the primary source of active power. This means that the wind energy system is intended to produce the active power needed to charge the BESS batteries and the active power needed by the grid to maintain the frequency at 50 Hz during periods of high wind speed.

The intermittent nature of the wind resource and potential outages (planned or unplanned) in the wind power plant are just two of the factors that could prevent the wind energy system from always being able to supply the entire amount of active power needed by the grid. The battery energy storage system is supposed to make up the shortfall and support the grid's balance when the wind energy system is unable to supply all of the active power needed.

The following table, Table 5.4, provides a description of the case studies which are simulated in this chapter. Three unique case studies were simulated, and the effectiveness of the developed active power control algorithm was tested. The simulated case studies imitate possible scenarios which can happen in real life at any time. The aim of this algorithm is to be always available to assist the grid with active power whenever there is a requirement, no matter the environmental or technical conditions.

Table 5.4: Description of the simulated case studies

Case study	Description
Case study 1	The load is increased by 15%. It is assumed that the wind speed is good, and all wind turbines are operating. The effectiveness of the developed active power algorithm is investigated.

Case study 2	The load is increased by 15%. It is assumed that there is a 50% outage at the WF which means that half of the WTs are not operating and the WF will not be able to supply the required active power on its own. The effectiveness of the developed active power algorithm is investigated.
Case study 3	The load is increased by 15%. It is assumed that the wind speed is fluctuating, which mean that the output power of the WF will fluctuate. The effectiveness of the developed active power algorithm is investigated.

5.5.2 Case Study 1: High Wind Speed Period

To prove the effectiveness of the control system developed for the participation of the wind energy system in active power reserve provision, case study 1 was simulated. For this case study, it is assumed that the wind energy system is performing at its best which means there is a good wind speed, and all wind turbines are operating. The developed control scheme is tested by simulating a system contingency whereby the load is ramped up by 15%. The 15% load increase contingency will be achieved by increasing the load by 1% in 15 steps separated by 10 seconds in terms of time. The contingency lasts for 150s and the simulated is ram for 200s. The remaining 50s is used to monitor the system after the contingency, if the load increase leads to a frequency dropping to a value of 49.4 Hz for example, we expect it to be constant at that value for the remaining 50s.

The diagram below, Figure 5.21, shows the waveform of the total active power demanded by the loads as the 15% load increase contingency was being applied. Initially, the total load demand was 315MW and after the contingency, the total load demand was recorded at 362.25MW. The load increased with a value of 47.25MW which is equal to 15% of the nominal load demand (315MW).

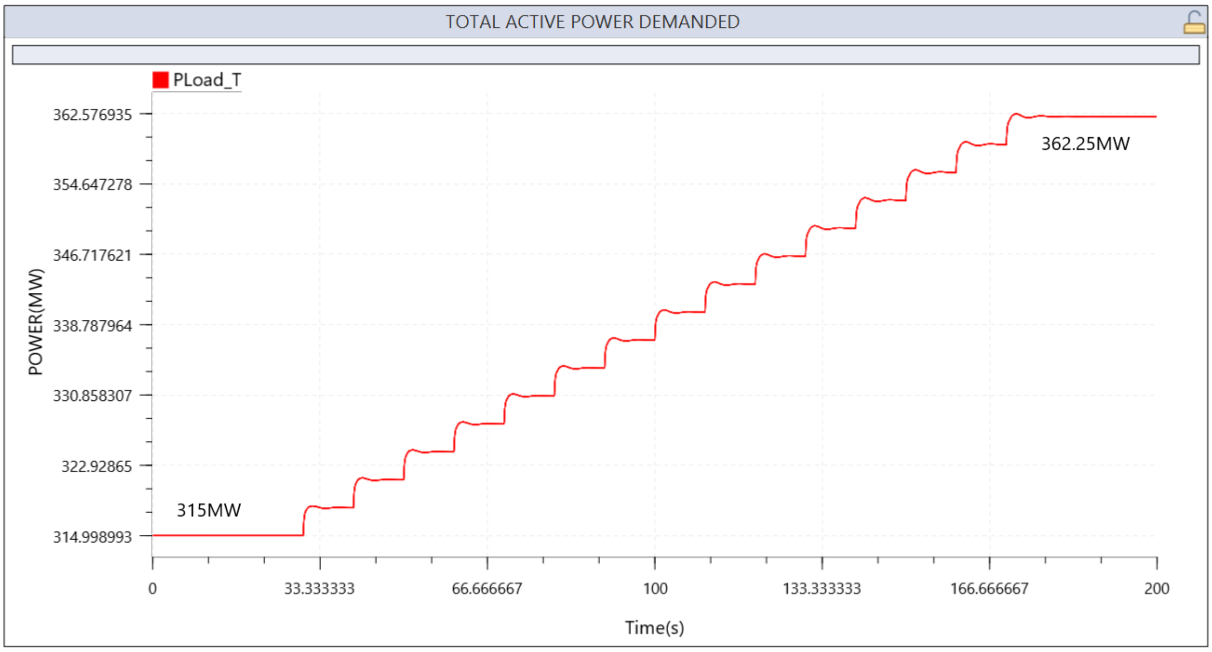


Figure 5.21: **Total active power demanded by the loads during the contingency**

The waveform of the active power produced by the wind energy system during the load rise contingency is depicted in the diagram below, Figure 5.22. In order to maintain the system frequency at 50Hz, the wind energy system increases its production constraint in response to the grid's active power requirements. Although the wind energy system was already connected to the grid prior to the emergency, it only produced 3.68 MW, which was utilized to replenish the batteries in the battery energy storage system. The power output of the wind energy system was measured to be 49.80MW following the contingency. This indicates that the necessary 47.25MW of active power reserves might be supplied by the wind energy system. The batteries are being charged using the extra electricity produced.

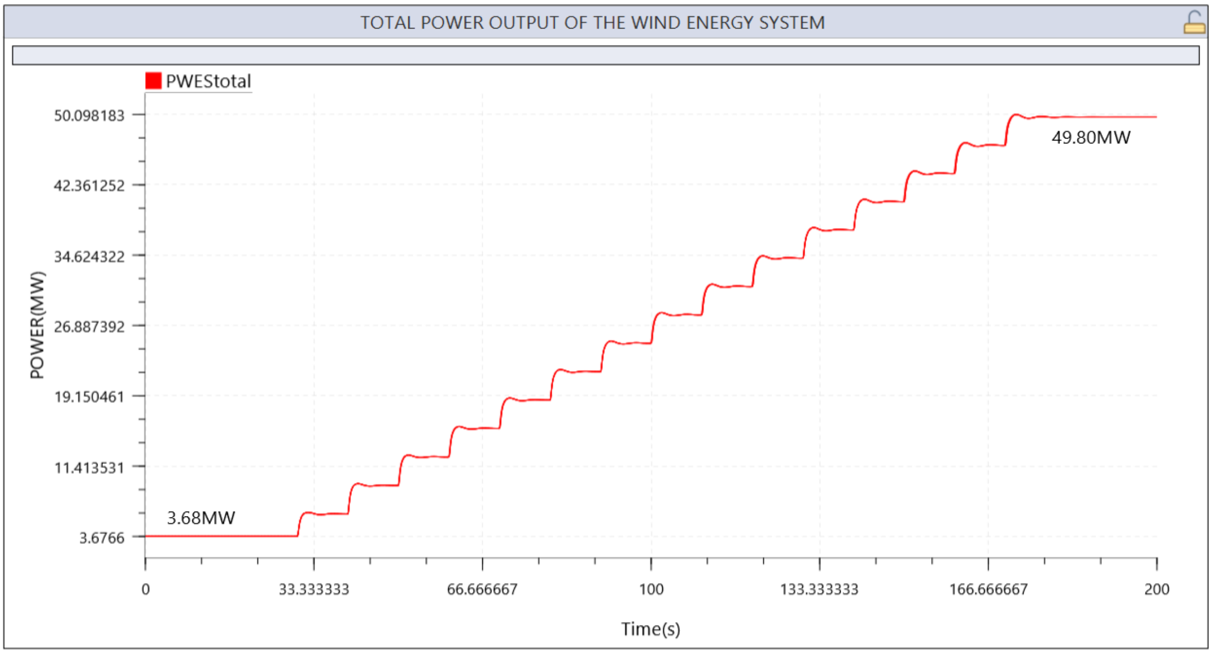


Figure 5.22: **Active power output of the wind energy system during the contingency**

Bidirectional power flow is supported by the battery energy storage system, allowing it to function in both charging and discharging modes. It uses the wind energy system to import active electricity as it charges. It only exports active electricity to the grid when it is discharging, which is only when the grid conditions demand it. The battery energy system's active power import or export waveform during the imposed load increase contingency is depicted in Figure 5.23, the diagram below. In this case study, the wind speed is sufficient for the WES to offset the active power without assistance, hence the BESS is importing from the WES.

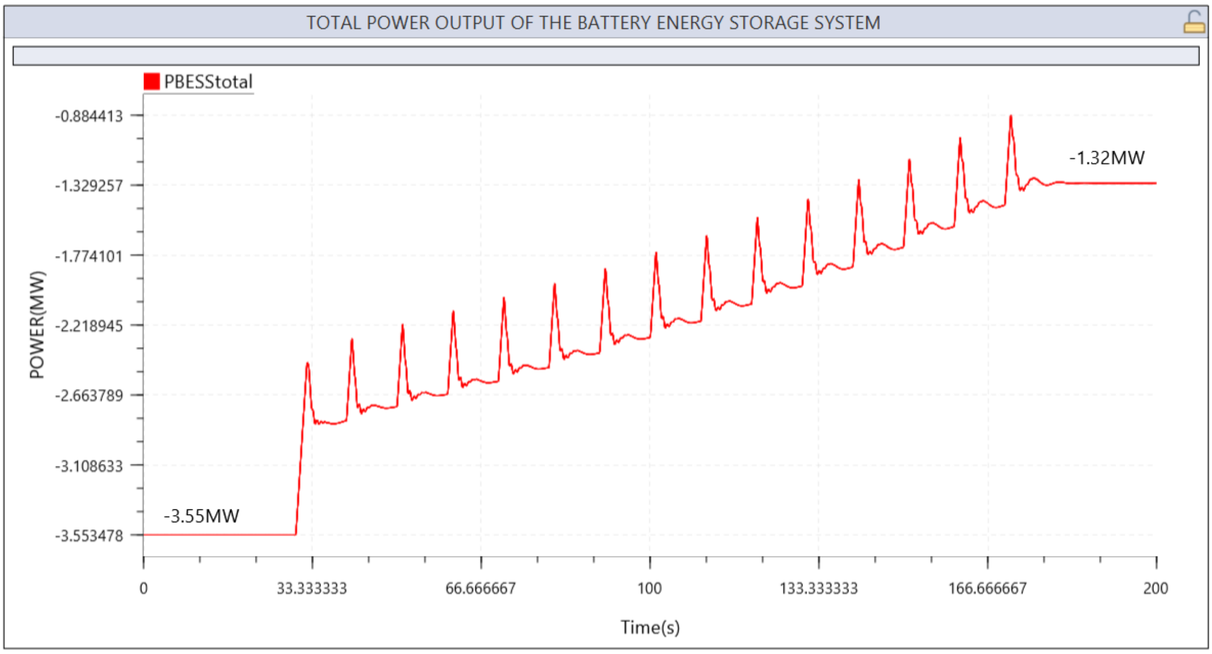


Figure 5.23: **Total active power imported/exported by the battery energy storage system**

The grid is represented by the waveform of the total active power produced by the three synchronous generators in Figure 5.24, the schematic below, during the application of the load increase contingency. Before the contingency was applied, the grid was generating 319.87MW. After the contingency, the grid was generating 312MW as shown on the waveform below. The active power generated by the grid increased by a value of approximately 1.13MW.

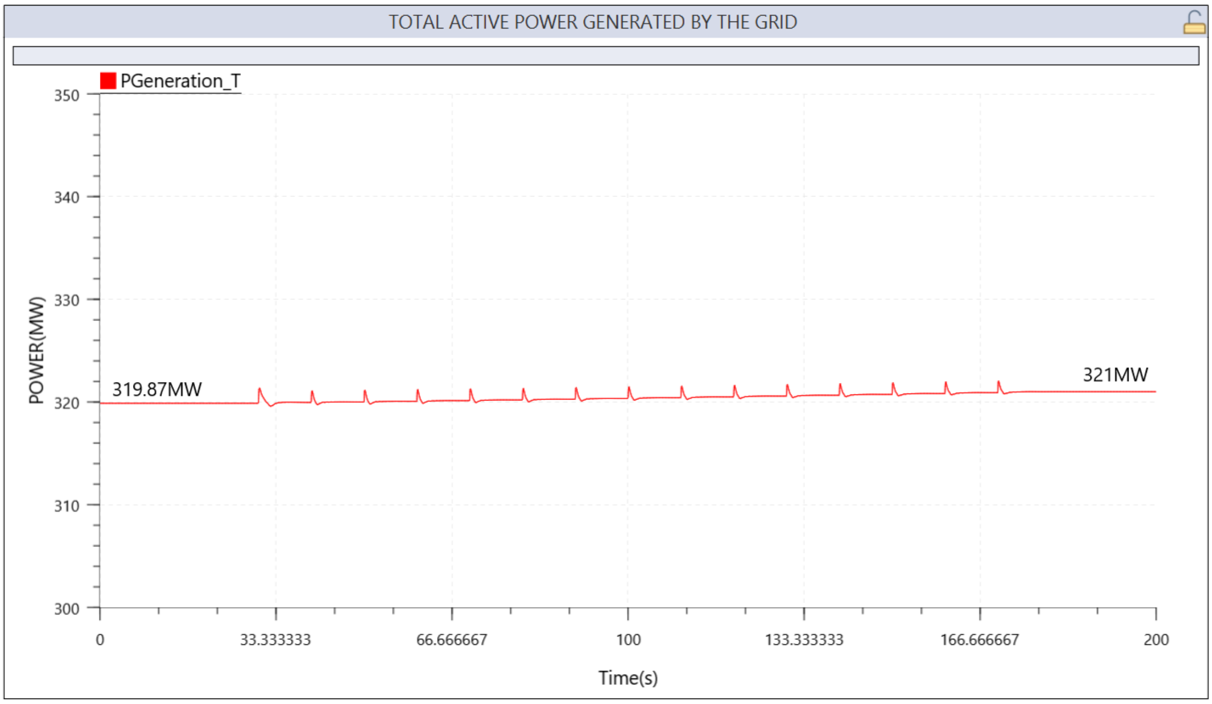


Figure 5.24: **Total active power generated by the grid**

The diagram below, Figure 5.25, shows the waveform of the system frequency which was being monitored as the load increase contingency was being applied. Before the contingency was simulated, the system frequency was measured at 50Hz. Following the load increase scenario, 49.99 Hz was recorded as the system frequency.

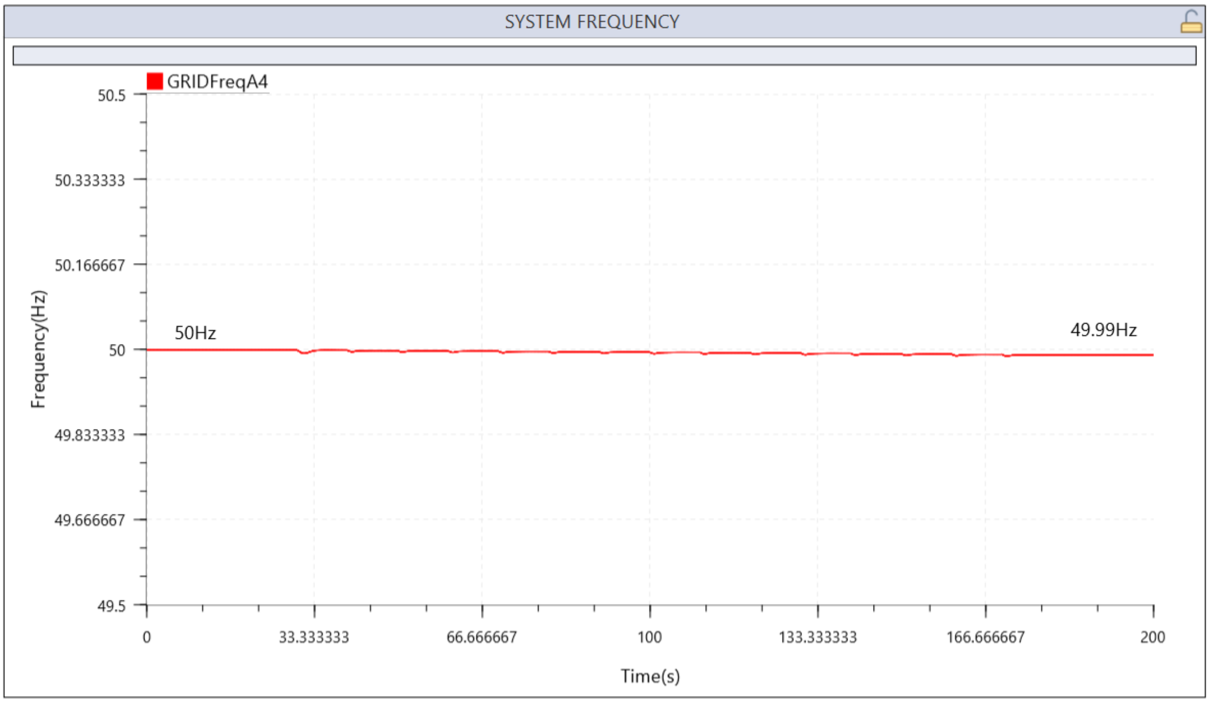


Figure 5.25: System frequency during the load increases contingency

The busbar voltage readings before and after the load increase simulation is implemented are displayed in Table 5.5. It is evident that there is not much of a difference between the readings taken before and after the dynamic state simulation. During load increase events, the voltage can be kept at steady state levels using the designed active power algorithm.

Table 5.5: Busbar voltages during the case study 1 contingency

Busbar	Voltage before (pu)	Voltage after (pu)
Bus 1	1.039	1.038
Bus 2	1.024	1.020
Bus 3	1.022	1.018
Bus 4	1.020	1.008
Bus 5	0.9913	0.9737
Bus 6	1.005	0.9881
Bus 7	1.021	1.012
Bus 8	1.011	0.9981
Bus 9	1.026	1.019

5.5.2.1 Discussion of results: Case Study 1

The first case study (case study 1) simulates a situation or condition whereby there is a load increases contingency and there is enough wind speed for the wind energy system to generate the required active power needed to compensate and balance the generation with load and maintain the frequency at 50Hz. For this case study, the battery energy system does not need to discharge and can charge if the wind energy system is capable of producing more than what is required by the grid.

The results for case study 1 are tabulated in Table 5.6 below. As can be seen from the table, when the contingency was simulated, the load increased from 315MW to 362.25MW and the total active power output of the wind energy system increased from 3.68MW to 29.28MW. The battery energy storage system remained in charging mode. The frequency decreased from 50Hz to 49.99Hz, which can be assumed to be an insignificant change. The power generated by the synchronous generators (grid) increased slightly by 1.13MW. The wind energy system managed to maintain the frequency at 50Hz during the load increase contingency for case study 1.

Table 5.6: **Case study 1 results (after implementation of control techniques)**

<table>
<tr><th colspan="2">Case study name</th><th colspan="4">Aim</th><th colspan="4">Type of disturbance</th></tr>
<tr><td colspan="2">Case study 1</td><td colspan="4">This case study proves the developed control system for the wind energy system is effective enough to stabilize the grid when the load demand increases to a value greater than the generation capacity.</td><td colspan="4">Load demand increased by 15% in steps of 1%</td></tr>
<tr><th colspan="10">Monitored variables</th></tr>
<tr><th colspan="2">Total load demand (MW)</th><th colspan="2">Total WES output (MW)</th><th colspan="2">Total BESS output (MW)</th><th colspan="2">System Frequency (Hz)</th><th colspan="2">Total Generation (MW)</th></tr>
<tr><td>before</td><td>after</td><td>before</td><td>after</td><td>before</td><td>after</td><td>before</td><td>after</td><td>before</td><td>after</td></tr>
<tr><td>315</td><td>362.25</td><td>3.68</td><td>49.80</td><td>-3.55</td><td>-1.32</td><td>50</td><td>49.99</td><td>319.87</td><td>321</td></tr>
</table>

5.5.3 Case Study 2: 50% Outage on the Wind Power Plant

Case study 2 was simulated in order to demonstrate the efficacy of the control system designed for the battery energy storage system's participation in the active power reserve provision. It is assumed for this case study that nearly half of the wind farm's installed wind turbines are unavailable due to planned maintenance outages. This means that only 8 turbines are running, and they can only provide a total of 29.44MW of active power. Should the grid require the whole 15% (47.25MW) of active power reserves, the battery energy storage system must supply the difference to balance the grid. The developed control scheme is tested by simulating a system contingency whereby the load is ramped up by 15%. The 15% load increase contingency will be achieved by increasing the load by 1% in 15 steps separated by 10 seconds in terms of time.

Figure 5.26, the diagram below, displays the waveform of the total active power consumed by the loads when the 15% load increase contingency was in effect. The total load demand was 315 MW at the beginning and 362.25 MW at the end of the contingency. A rise in load was observed, reaching 47.25 MW, or 15% of the nominal load demand of 315 MW.

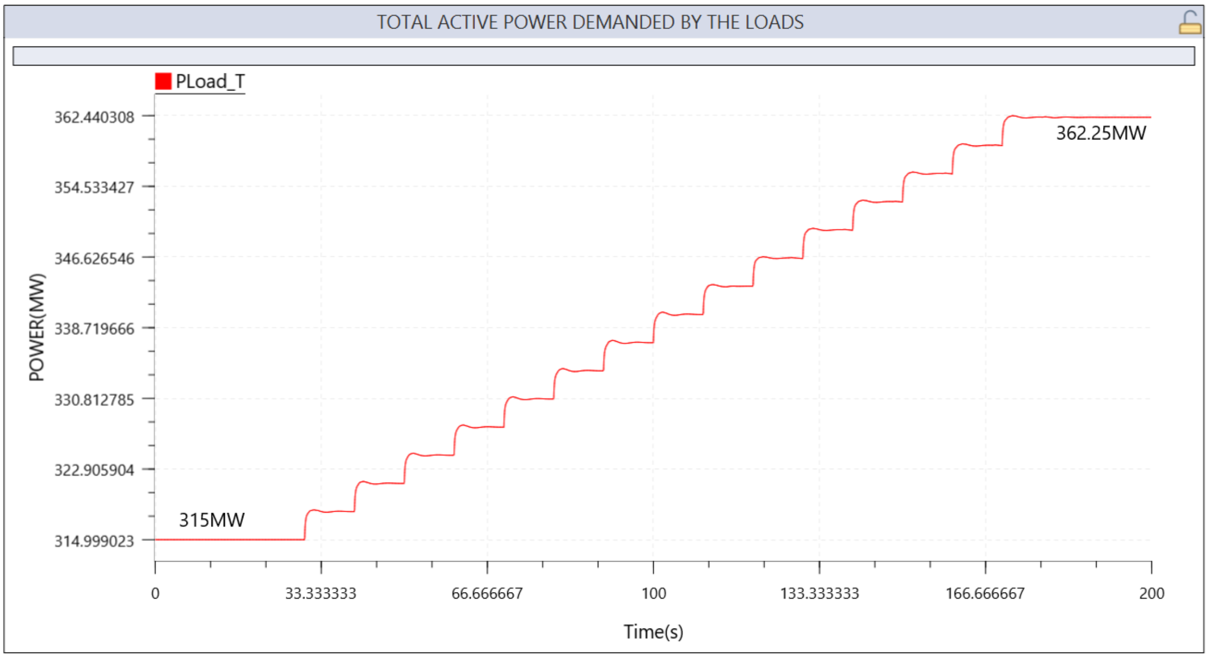


Figure 5.26: **Active power demanded by the loads after the contingency**

The wind energy system's active power waveform during the load increase contingency is depicted in Figure 5.27, the diagram below. In response to the grid's need for active power to maintain the system frequency at 50 Hz, the wind energy system increases its production constraint. The 3.68MW of power that the wind energy system produced before the emergency was connected into the grid and used to recharge the batteries of the battery energy storage system. The power output of the wind energy system was measured to be 29.28MW following the contingency. This indicates that because 50% of the wind turbines in the system are experiencing an outage, the system has not been able to provide the necessary 47.25MW of active power reserves. The battery energy storage system must step in at this point, make up the shortfall in active power, and balance the power required and created.

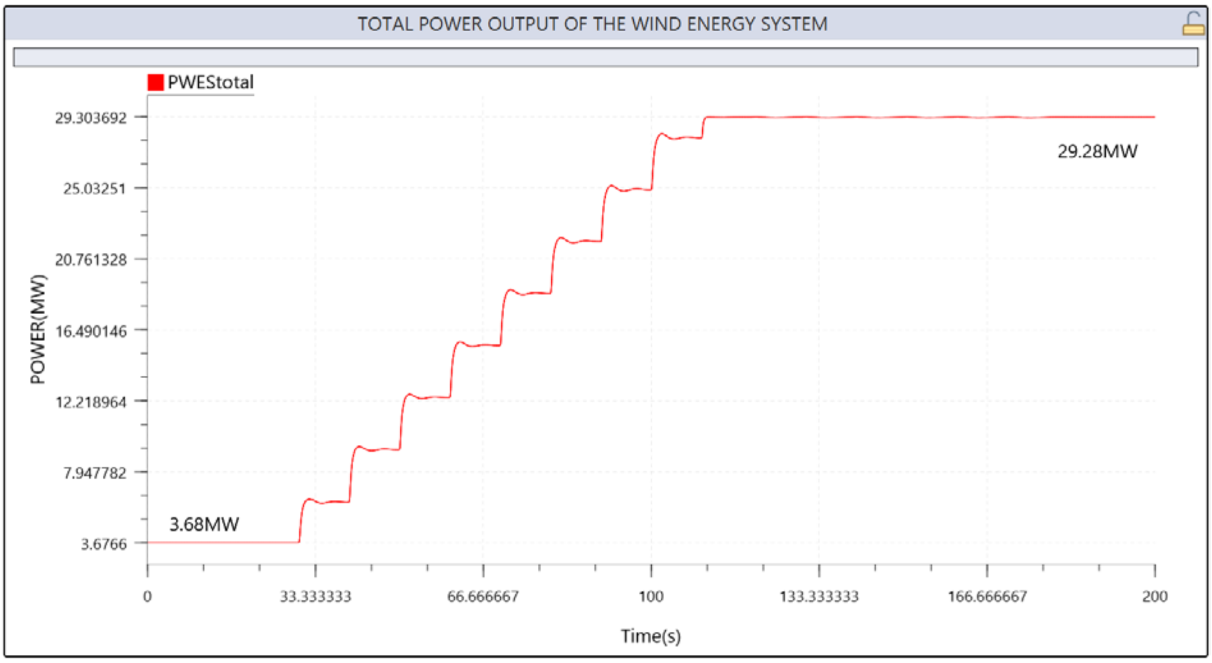


Figure 5.27: Active power output of the wind energy system after the load increase contingency

The battery energy storage system's active power output waveform as the load increase contingency was applied is seen in the diagram below, Figure 5.28. 3.55 MW was being imported and charged by the battery energy storage system before to the emergency. Following the event, the energy storage system based on batteries was exporting and discharging 19.17 MW. Around 110s, the BESS replaces the WES and provides the energy needed to maintain grid stability, which is the difference between the WES's output power and the required active power.

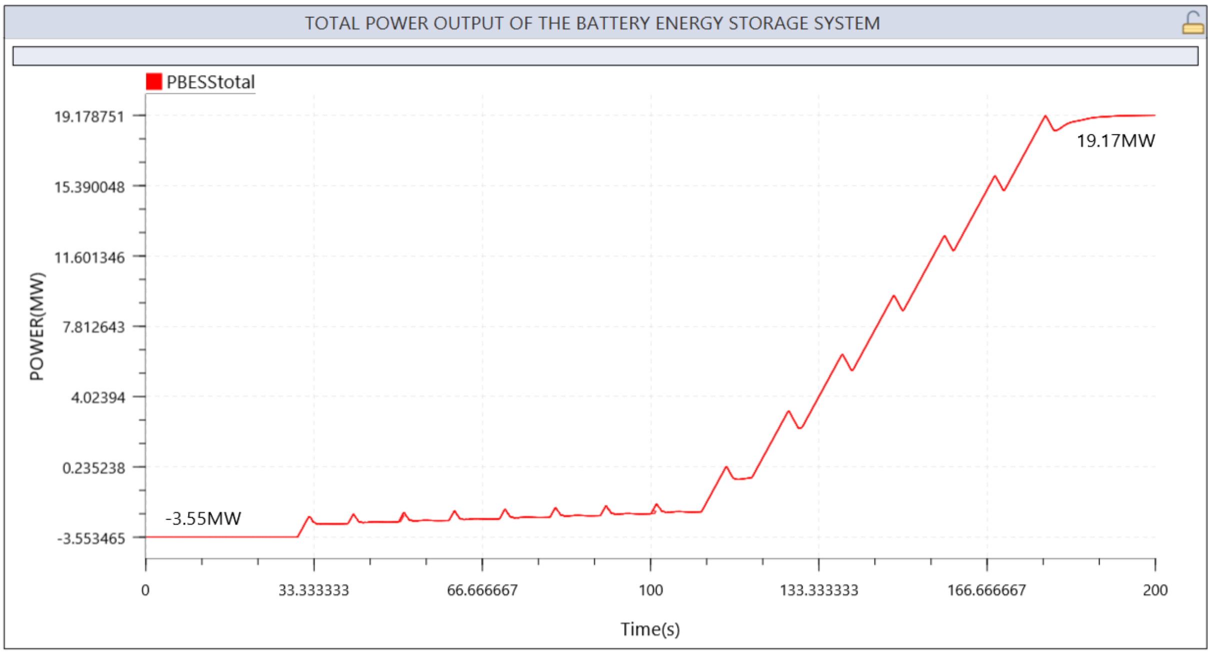


Figure 5.28: Active power output of the BESS during the contingency

The grid is represented by the waveform of the total active power produced by the three synchronous generators in Figure 5.29, the diagram below, during the application of the load increase contingency. Before the contingency was applied, the grid was generating 319.87MW. After the contingency, the grid was generating 321MW as shown on the waveform below. The active power generated by the grid increased by a value of approximately 1.13MW.

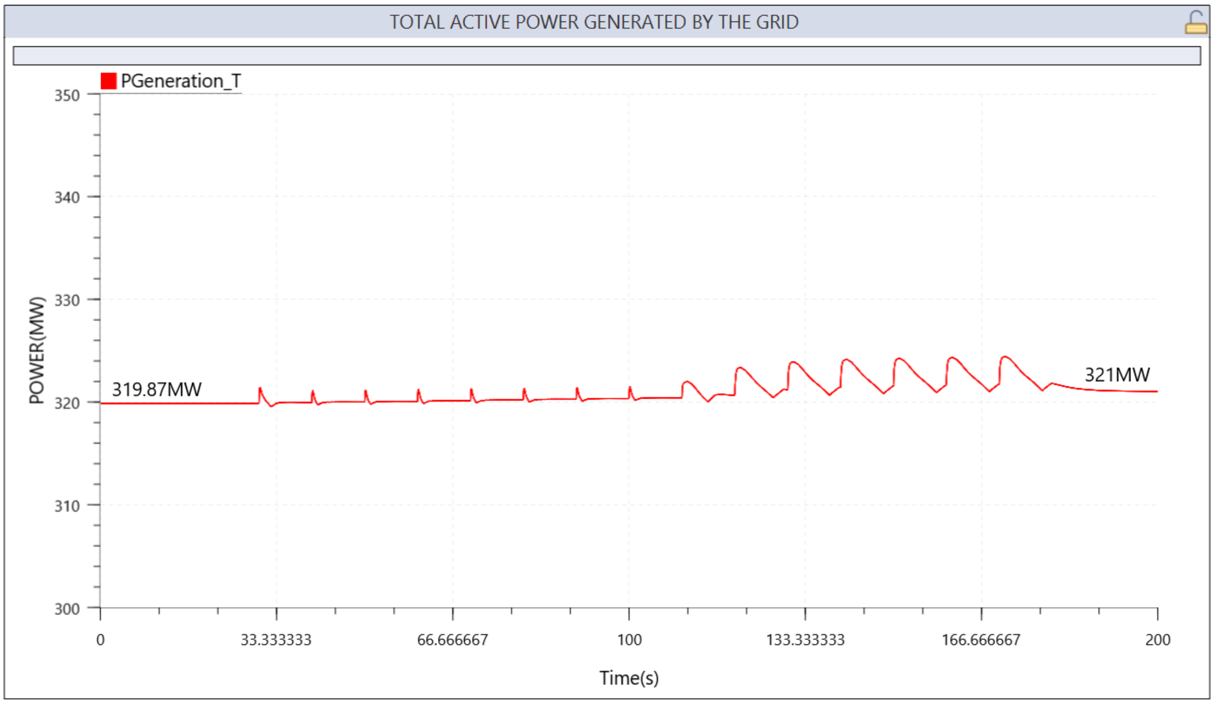


Figure 5.29: **Total active power generated by the grid during contingency**

The diagram below, Figure 5.30, shows the waveform of the system frequency which was being monitored as the load increase contingency was being applied. Before the contingency was simulated, the system frequency was measured at 50Hz. The system frequency was recorded at 49.99 Hz following the load increase contingency.

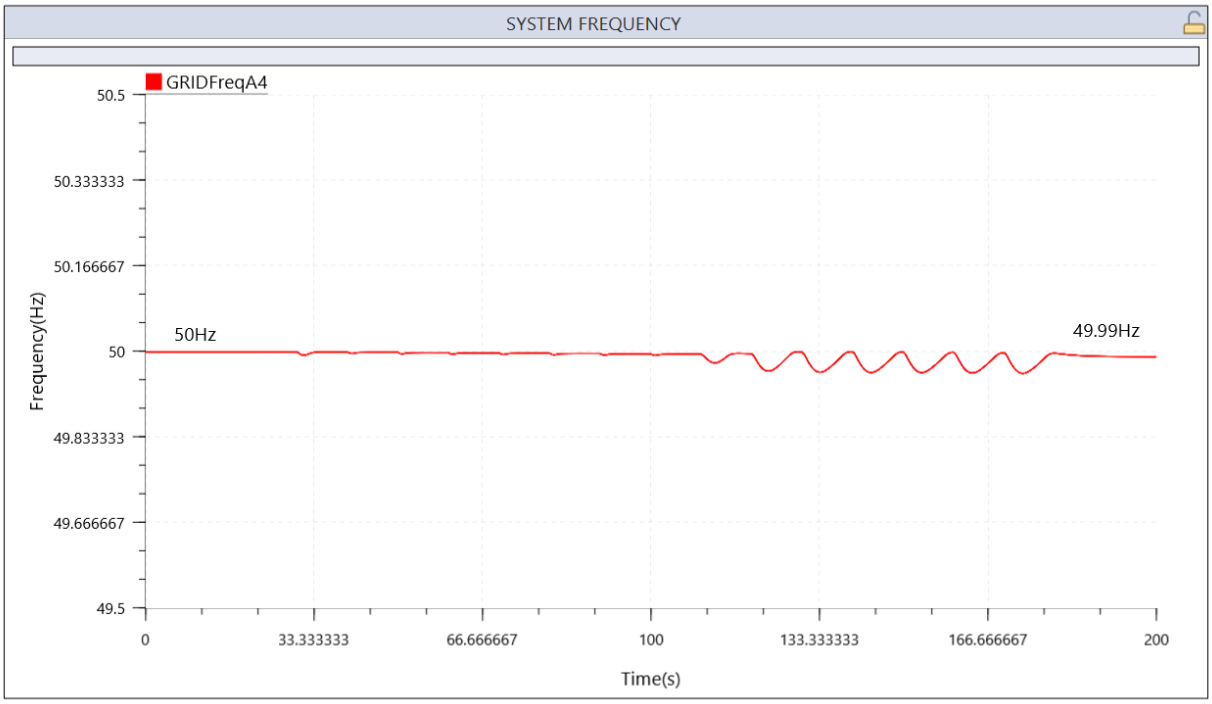


Figure 5.30: System frequency during the contingency

The busbar voltage readings both before and after the load increase simulation is implemented are displayed in Table 5.7. It is evident that there is not much of a difference between the readings taken before and after the dynamic state simulation. During load increase events, the voltage can be kept at steady state levels using the designed active power algorithm.

Table 5.7: Busbar voltages during the case study 2 contingency

Busbar	Voltage before (pu)	Voltage after (pu)
Bus 1	1.039	1.038
Bus 2	1.024	1.021
Bus 3	1.022	1.018
Bus 4	1.020	1.008
Bus 5	0.9913	0.9736
Bus 6	1.005	0.9879
Bus 7	1.021	1.011
Bus 8	1.011	0.9978
Bus 9	1.026	1.016

5.5.3.1 Discussion of results: Case Study 2

The second case study (case study 2) simulates a situation whereby there is a load increase contingency during an outage of half of the wind power plant. In this case, the wind energy system is not able to provide the total active power reserves required, and the battery energy system is expected to take over and supply the deficit.

The results for case study 2 are tabulated in Table 5.8 below. As can be seen from the table, when the contingency was simulated, the load increased from 315MW to 362.25MW and the total active power output of the wind energy system increased from 3.68MW to 29.28MW. At the beginning of the simulation, the battery energy storage system was operating in charging mode and later changed to discharging mode when the wind energy system could no longer provide more active power. The power output of the BESS increased to 19.17MW, making the total active power generated by both the BESS and WES equal to 48.45MW. The frequency decreased from 50Hz to 49.99Hz, which can be assumed to be an insignificant change. The power generated by the synchronous generators (grid) increased slightly by 1.13MW. The wind energy system together with the battery energy storage system managed to maintain the frequency at 50Hz during the load increase contingency for case study 2.

Table 5.8: **Case study 2 results (after implementation of control techniques)**

<table>
<tr><th colspan="2">Case study name</th><th colspan="4">Aim</th><th colspan="4">Type of disturbance</th></tr>
<tr><td colspan="2">Case study 2</td><td colspan="4">This case study proves the developed control system for the battery energy storage system is effective enough to stabilize the grid when the load demand increases to a value greater than the generation capacity.</td><td colspan="4">Load demand increases by 15% in steps of 1% and 50% of the wind farm is out on outage.</td></tr>
<tr><th colspan="10">Monitored variables</th></tr>
<tr><th colspan="2">Total load demand (MW)</th><th colspan="2">Total WES output (MW)</th><th colspan="2">Total BESS output (MW)</th><th colspan="2">System Frequency (Hz)</th><th colspan="2">Total Generation (MW)</th></tr>
<tr><td>before</td><td>after</td><td>before</td><td>after</td><td>before</td><td>after</td><td>before</td><td>after</td><td>before</td><td>after</td></tr>
<tr><td>315</td><td>362.25</td><td>3.68</td><td>29.28</td><td>-3.55</td><td>19.17</td><td>50</td><td>49.99</td><td>319.87</td><td>321</td></tr>
</table>

5.5.4 Case study 3: Variation of the wind speed

The wind energy resource is known for its intermittent nature, the wind speed can drop or increase at any time. The developed control techniques must be able to successfully restore and maintain the system frequency at 50Hz should there be a decrease in wind speed during moments of high load demand. For this case study, it is assumed that the wind speed drops gradually from 14m/s to 8m/s and rises again back to 14m/s. The grid is assumed to have experienced a load demand increase of 15% which will remain constant until the end of the simulation. When the wind speed drops, the wind energy system may not be able to provide the total active power required by the grid to maintain the system frequency at 50 Hz. Therefore, the battery energy storage system is expected to discharge when the wind speed drops. The developed control scheme is tested by simulating a system contingency whereby the load is ramped up by 15%.

The diagram below, Figure 5.31, shows the waveform as it was scheduled to automatically drop from 14m/s to 8m/s and rise back up to 14m/s. A scheduler was modelled on RSCAD to achieve this to avoid doing it manually on RSCAS Runtime. The main aim of this is to control or decrease the power output of the wind energy system using wind speed.

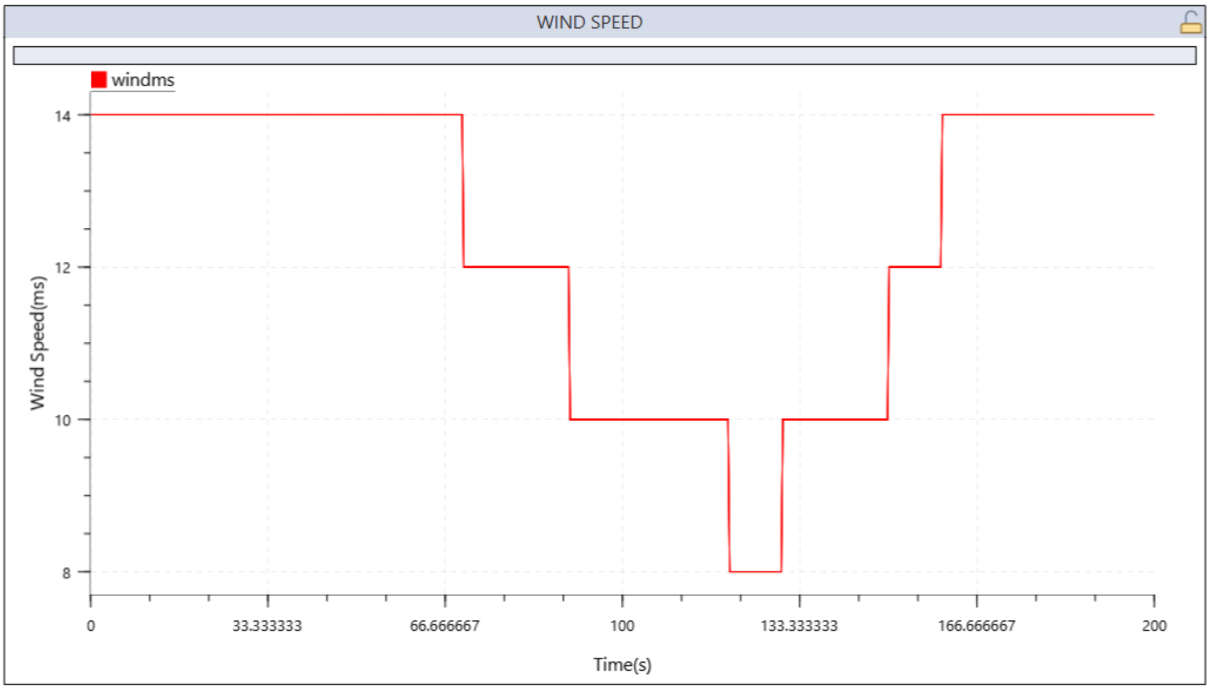


Figure 5.31: **Wind speed variation waveform**

Figure 5.32 illustrates the waveform of the total active power consumed by the loads while the 15% load increase contingency was in effect. The overall load demand was 315 MW at the beginning of the contingency, and it was reported as 362.26 MW at the end. With a load increase of 47.26 MW, the load is 15% of the nominal load demand (315 MW).

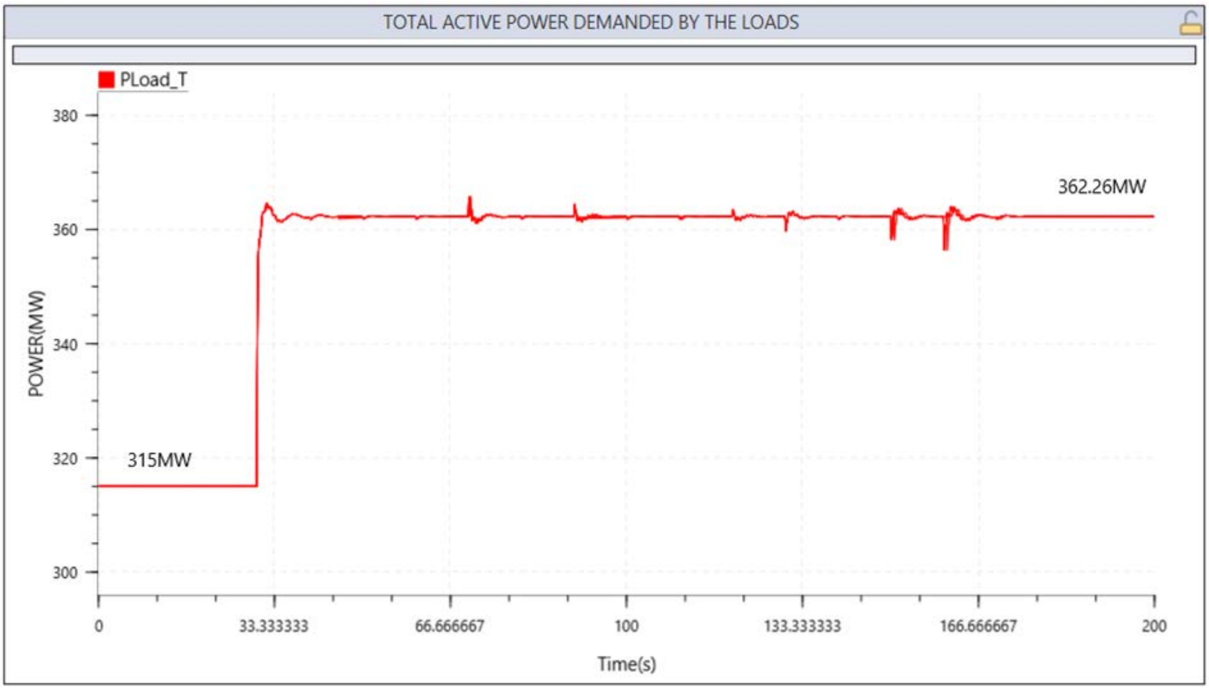


Figure 5.32: Total active power consumed by all the loads

The wind energy system's active power waveform during the load increase contingency is depicted in Figure 5.33, the schematic below, while the speed was changed. In response to the grid's need for active power to maintain the system frequency at 50 Hz, the wind energy system increases its production constraint. The 3.68MW of wind energy that the wind energy system produced before to the emergency was utilized to recharge the batteries of the battery energy storage system. Following the emergency, 49.80MW of power was produced by the wind energy system. Less than the necessary 47.26MW was produced by the wind energy system when the wind speed was reduced to 8 m/s. In this situation, the battery energy storage system must step in, make up the difference in active power, and balance the amount of power required and produced.

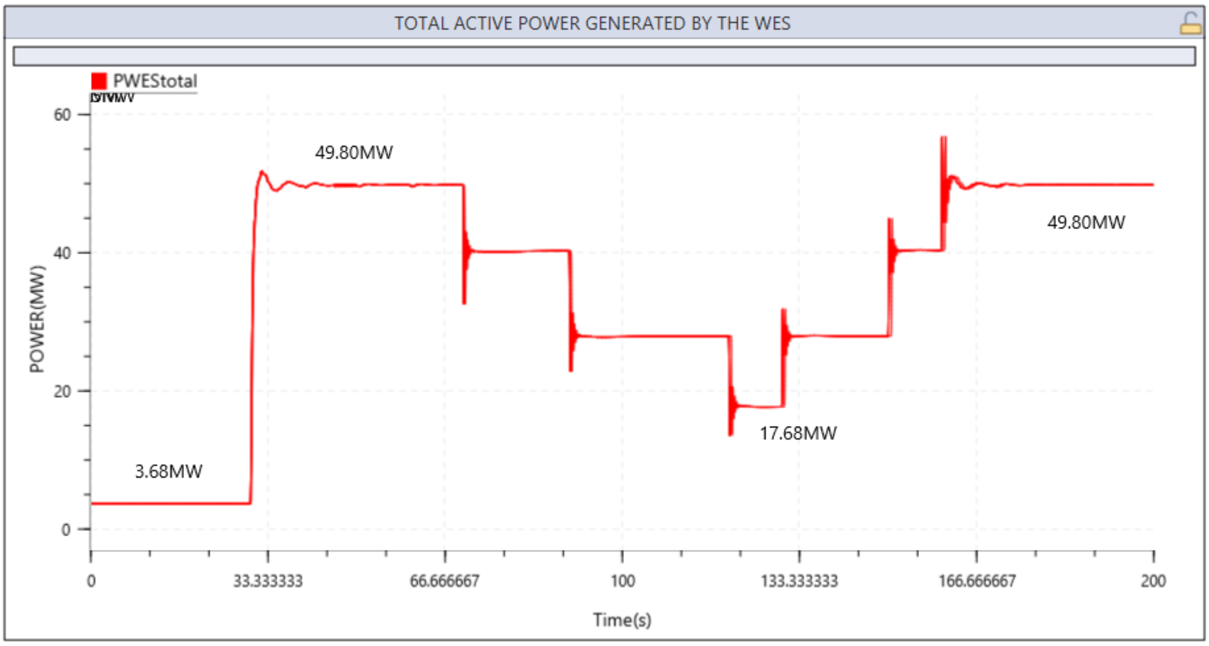


Figure 5.33: Active power output generated by the wind energy system

The battery energy storage system's active power output waveform as the load increase contingency was applied is seen in the diagram below, Figure 5.34. 3.55 MW was being imported and charged by the battery energy storage system before to the emergency. The BESS began to import and discharge active electricity into the grid as the wind speed began to decrease. The output power produced by the BESS peaked at 25 MW. Following the emergency, the wind energy system supplied the entire active power needed to stabilize the grid, allowing the wind speed to return to the intended level. The battery energy storage system was charged at a rate of -1 MW.

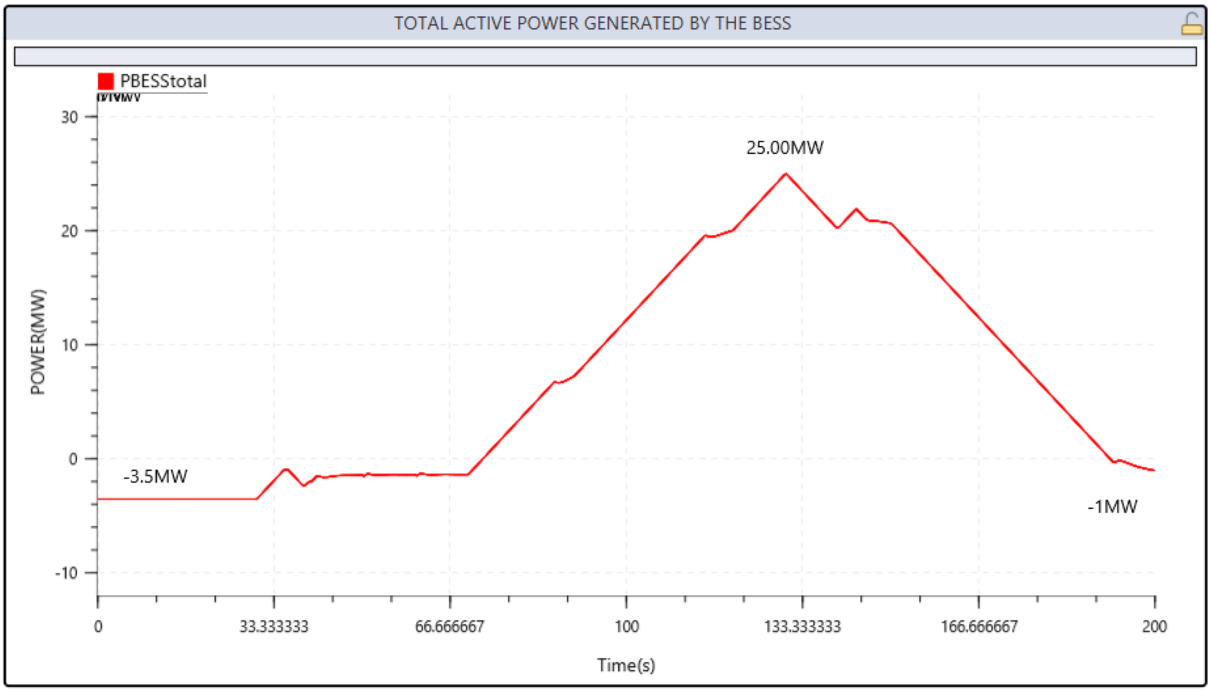


Figure 5.34: Active power discharged from the battery energy storage system

The grid is depicted in Figure 5.35, the graphic below, as the waveform of the total active power produced by the three synchronous generators when the wind speed was being adjusted and the load increase contingency was being applied. Before the contingency was applied, the grid was generating 319.87MW. After the contingency, the grid was generating 320.53MW as shown on the waveform below. The active power generated by the grid increased by a value of approximately 0.66MW which is almost insignificant.

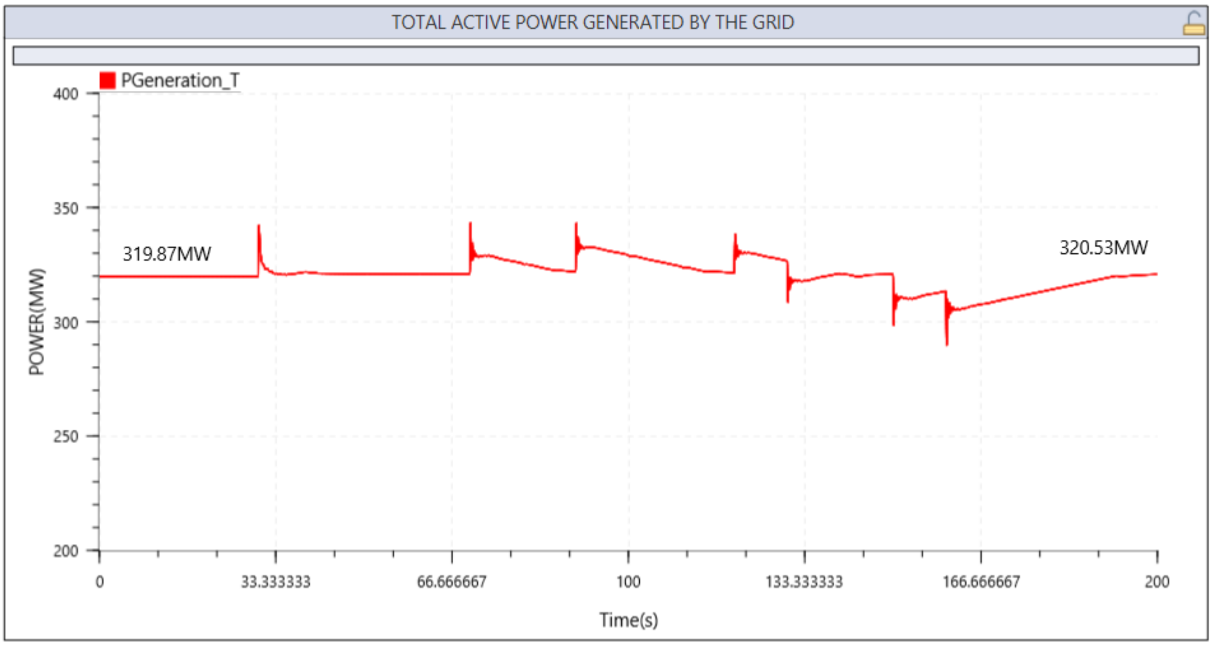


Figure 5.35: Active power generated by the synchronous generators

Figure 5.36, the graphic below, displays the waveform of the system frequency that was being observed while the load increase contingency was being implemented. The system frequency was measured at 50Hz prior to simulating the scenario. The system frequency was recorded at 49.99 Hz following the load increase contingency.

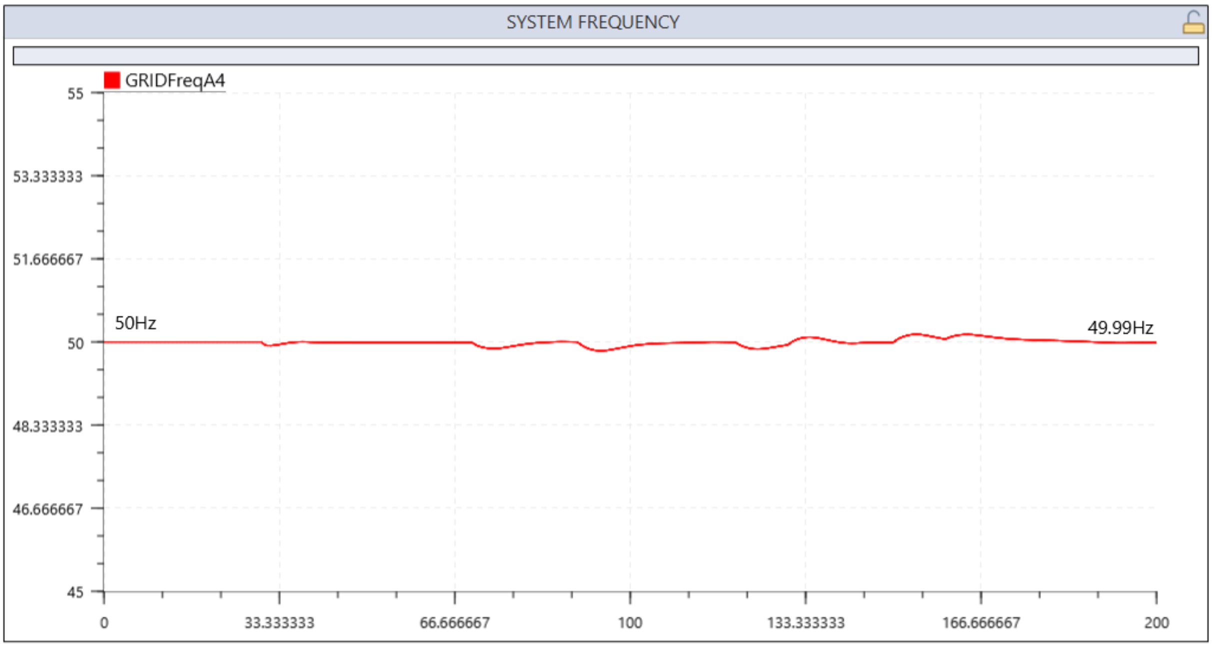


Figure 5.36: System frequency throughout the grid contingency

Table 5.9 presents the busbar voltage readings both prior to and subsequent to the load increase simulation. There is not much of a difference between the readings before and after the dynamic state simulation, as can be shown. The voltage can be kept at steady state levels even when there are load increase events thanks to the created active power algorithm.

Table 5.9: Busbar voltages during the case study 3 contingency

Busbar	Voltage before (pu)	Voltage after (pu)
Bus 1	1.039	1.038
Bus 2	1.024	1.022
Bus 3	1.022	1.018
Bus 4	1.020	1.008
Bus 5	0.9913	0.9736
Bus 6	1.005	0.9882
Bus 7	1.021	1.011
Bus 8	1.011	0.9978
Bus 9	1.026	1.017

5.5.4.1 Discussion of results: Case Study 3

The third case study (case study 3) mimics a scenario in which the wind speed varies, causing the wind energy system's output power to fluctuate as well. In this instance, the battery energy system is anticipated to step in and make up the shortfall as the wind energy system is unable to offer the entire amount of active power reserves needed.

Table 5.10 below contains a tabulation of the case study 3 data. The table shows that when the contingency was simulated, the wind energy system's total active power output grew from 3.68MW to 49.80MW, while the load increased from 315MW to 362.26MW. The wind speed returned to the intended level at the end of the contingency, and the BESS was operating in charging mode at -1MW. The frequency dropped from 50 Hz to 49.99 Hz, which is probably a negligible difference. The grid's (synchronous generators') electricity output increased marginally by 0.66 MW. During the case study 3 load increase contingency, the wind energy system and the battery energy storage system were able to keep the frequency at 50 Hz.

Table 5.10: Case study 3 results (after implementation of control techniques)

Case study name	Aim	Type of disturbance
Case study 3	This case study proves the developed control system for the battery energy storage system is effective enough to stabilize the grid when the load demand increases to a value greater than the generation capacity.	Load demand increases by 15% in steps of 1% and the wind speed is fluctuating.

Monitored variables									
Total load demand (MW)		**Total WES output (MW)**		**Total BESS output (MW)**		**System Frequency (Hz)**		**Total Generation (MW)**	
before	after	before	after	before	after	before	after	before	after
315	362.26	3.68	49.80	-3.55	-1.00	50	49.99	319.87	320.53

5.6 Conclusion

Two case studies were simulated to emphasize the need for and importance of active power operating reserves in the grid. A wind energy system together with a battery energy system is proposed as a solution to provide active power operating reserves during grid contingencies. The wind energy system and the battery energy storage system were modelled and integrated into the modified IEEE 9 bus system. An active power control technique was developed to dispatch the active power reserves from the WES and BESS during grid contingencies. Three unique case studies were simulated to test the effectiveness of the developed control techniques. The first case study simulated a condition whereby there is a load increase contingency during a period of high wind speed. The second case study simulates a condition whereby a load increase contingency hits the power system network at a moment when 50% of the wind power plant dedicated for active power provision is out on outage. The third and the last case study simulates a situation where the wind speed is fluctuating, the load demand is increased by 15% and is kept constant until the end of the contingency. In all three simulated case studies, the developed active power control algorithm responded successfully by dispatching the required active power from the WES and/or the BESS to balance the demand and supply of the electricity grid.

CHAPTER SIX

DELIVERABLES, CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

For an electric power utility that serves load, there are two main sources of uncertainty. For several reasons, including weather, the actual load may be much higher than the anticipated load. On the other side, forced or unplanned interruptions of a utility's generation units could lower total generating availability. A utility maintains a reserve margin to cover these potential risks. The amount of generating capacity that is available above peak demand is known as the reserve margin. The ideal reserve margin is determined by the composition and size of a load-serving entity.

As renewable-based power plants (like wind and solar) replace traditional generators, the quantity of power reserves offered by traditional generators declines. Wind power plants therefore need to supply power reserves, exactly like conventional producing units. Although the amount of power generated by wind plants is largely dependent on the unpredictable and fluctuating wind speed, research indicates that wind energy systems can supply power reserves and, as a result, contribute to grid frequency control when properly implemented. In power systems, battery energy storage technologies have gained a lot of traction in the last few years. Recently, technological advancements and cost reductions have occurred in BESS. Power utilities can convert variable wind power generation into dispatchable technology by integrating wind farms with battery energy storage systems. This allows the technology to help supply ancillary services that non-dispatchable technologies are typically unable to deliver.

This dissertation covers how wind energy systems together with battery energy storage systems can work together to participate in active power operating reserves in a deregulated electricity market. A control scheme to enable the wind energy system and the battery energy storage system to dispatch power to the grid when needed was developed using the RSCAD simulation package. The efficacy of the developed control scheme was assessed using various disturbance contingencies.

This chapter is structured as follows: section 7.1 is the introduction of the chapter, followed by Section 7.2, which covers the aim and objectives of the research study, and section 7.3 covers the overall deliverables of the dissertation in summarized form. Section 7.4 describes how the work covered in this dissertation can be utilized for academic and industrial advancement. Section 7.5 outlines the future work that can be conducted concerning this topic of interest. And finally, section 7.6 covers the list of publications developed from the achievement of this dissertation output.

6.2 Aims and Objectives

This study builds on the knowledge that wind power plants are the increasing alternative renewable source of energy, as well as on the information about the integration of such renewable energy sources to the power system grid to provide operating reserves.

The goal of this study is to look at South Africa's electrical reserves margin and storage capacity. Then, to improve the power market, model, simulate, and analyze a wind energy system and battery energy storage system with reserve capacity. The following is a list of objectives on how the aim is fulfilled:

i. Research about the literature review on operating energy reserve and its price benefits
ii. Study literature review on power quality benefits with reserve margin.
iii. Analysis of South African operating reserve methodology and its implementation.
iv. Study the theory on energy reserve and its methods adopted nationally and globally.
v. Formulate the mathematical equations to calculate the electricity market with wind and battery storage by considering the reserve margin.
vi. Develop an energy reserve algorithm with a wind energy system and battery storage system and analyze electricity markets.
vii. Model, simulate, and analyze the south African power systems network with wind, and battery model with allocated reserve margin. Conduct detailed electricity market investigations with different case studies in the RSCAD software suite for the RTDS simulation package.

6.3 Dissertation deliverables

This section covers the summary of the work performed to achieve the aim and objectives of the research study.

6.3.1 Chapter 2: Literature Review

According to the literature review, there is a need to develop and execute control schemes on different power system simulation platforms to validate proposed philosophies. The goal of the proposed research is to create a control strategy that will allow the battery energy storage system and the wind energy system to dispatch active power during grid emergencies as needed by the grid to keep the system frequency steady within allowable bounds. Furthermore, it has been noted in the literature reviewed that there needs to be more work on control development studies using the RSCAD simulation platforms. Therefore, this research study will also contribute immensely to the utilization of the RSCAD simulation platforms in the modelling and development of control schemes.

6.3.2 Chapter 3: Theoretical framework

The theory developed in this thesis explains some of the key concepts of operating reserves in power systems. The theory also dives into wind energy systems, battery energy storage systems and the deregulation of the electricity market. The theory covers the advantages and disadvantages of both wind energy systems and battery energy storage systems and assesses their capabilities in reserve provision. The online digital library, books, and other sources contain theories about the operating reserves and their possibilities of being provided by wind energy systems and battery energy storage systems.

6.3.3 Chapter 4: Modelling and simulation of the IEEE 9 bus system on RSCAD

One of the requirements in power system stability studies is the selection of the power system network model. For this reason, the IEEE Nine-bus system was selected, and modelled and simulations cases were conducted for normal load flows and increased load demand contingency when the challenges the power systems undergo in terms of frequency and voltage stability were investigated. This chapter provides a discussion and analysis of all the results obtained in chapter 4.

6.3.4 Chapter 5: Modelling of the WES and BESS and coupling to the IEEE 9 bus power system

The wind power plant was modelled using the data from Vestas for a wind turbine model, and the literature by the reference for a squirrel-cage induction generator (SCIG). The battery energy storage system model was adopted from the modelling examples as provided on the RSCAD simulation package. In this chapter, control techniques that enable the wind energy system and the battery energy storage system to participate in active power reserve provision by dispatching the required active power to maintain the frequency at 50Hz were developed. The wind power plant and the battery energy storage system were integrated into the IEEE Nine-bus power system. The increased load demand contingencies were implemented. The load increase contingencies were simulated to investigate the effectiveness of the developed control scheme in dispatching the required active power to balance the grid from both the wind energy system and the battery energy storage system. Three different scenarios were simulated in this chapter. This chapter also provides a discussion and analysis of all the results obtained in chapter 5.

6.4 Academic and Industrial Applications

The knowledge presented in this dissertation will help the power system planners and operators from utility companies and private entities to make an informed decision about active power reserve provision. The provision of active power reserves from wind energy systems and battery energy storage systems can speed up the process of deregulation of the South African electricity market. The research study provides a detailed approach to utilizing both wind energy systems and battery energy storage systems in operating reserve provision. The developed control scheme will also help utility companies exploit as much power as possible from wind energy systems and battery energy storage systems to enhance grid stability and reliability.

In the academic space, the knowledge presented in this dissertation can help to build a foundation for power system researchers to understand the possibilities of renewable energy sources like wind energy participating in operating reserve provision; furthermore, this study can be used as a reference to further research studies. This study will teach undergraduates about the steps to follow when modelling wind turbines and wind turbine generators, squirrel cage induction generators to be specific.

6.5 Future work

In the future, hardware development of the proposed control scheme can be performed to assess the efficacy of the control scheme in real time. Furthermore, the automation system for active power reserve dispatch from renewable energy sources is also one of the gaps, and the proposed control scheme hardware can be integrated with the automatic service restoration control loop.

6.6 Publications

6.6.1 Conference publications

1. S. J. Mndiya, M. Ratshitanga and S. Krishnamurthy, "The role of WES and BESS in the provision of operating electricity reserves-a review," 2024 32nd Southern African Universities Power Engineering Conference (SAUPEC), Stellenbosch, South Africa, 2024, pp. 1-6, doi: 10.1109/SAUPEC60914.2024.10445084.

2. S. J. Mndiya, M. Ratshitanga and S. Krishnamurthy, (2024). “Active power reserve provision with large-scale WES and BESS.” Accepted for the 11th IEEE PES & IAS PowerAfrica Conference (PAC 2024).

6.7 Summary

This chapter summarizes the objective and expected deliverables of the research study. Extensive and systematic literature reviews were conducted, and the theoretical aspects of the topic were also considered. The Real-time digital Simulator Computer-Aided Design (RSCAD) simulation software was used to perform the model and simulations as described in the chapter. The academic and industrial contributions of the research work are highlighted, along with future considerations for advancing the work. Additionally, publications such as journals and conferences are mentioned, and a list of references consulted for this dissertation is included in this chapter.

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APPENDICES

Appendices A to G provide the basecase plant model data for the IEEE 9bus system as follows:

APPENDIX A: Transformer Data

From BUS	To BUS	R (pu)	X (pu)	Tap Ratio
1	8	0.0	0.0576	1.0
2	4	0.0	0.0625	1.0
3	9	0.0	0.0586	1.0

Where:
R(pu) is the positive/zero sequence resistance, and
X(pu) is the positive/zero sequency reactance.

APPENDIX B: Generator Data-Part 1 (100 MVA Base)

GEN	BUS	Xa (pu)	Xd (pu)	Xd' (pu)	Xd" (pu)	Xq (pu)	Xq' (pu)	Xq" (pu)
1	1	0.01460	0.1460	0.0608	0.06	0.1000	0.0969	0.06
2	2	0.08958	0.8958	0.1198	0.11	0.8645	0.1969	0.11
3	3	0.13125	1.3125	0.1813	0.18	1.2578	0.2500	0.18

Where:
Xa(pu) is the stator leakage reactance,
Xd(pu) is the D-axis: unsaturated reactance,
Xd’(pu) is the D: unsaturated transient reactance,
Xd”(pu) is the D: unsaturated sub-transient reactance,
Xq(pu) is the Q-axis unsaturated reactance,
Xq’(pu) is the Q-axis: unsaturated reactance, and
Xq”(pu) is the Q: unsaturated sub-transient reactance.

APPENDIX C: Generator Data-Part 2 (100 MVA Base)

GEN	BUS	Ra (pu)	Tdo' (s)	Tdo" (s)	Tqo' (s)	Tqo" (s)	H (s)	D(pu/pu)
1	1	0.000125	8.96	0.01	0.310	0.01	23.64	0.0
2	2	0.000125	6.00	0.01	0.535	0.01	6.40	0.0
3	3	0.000125	5.89	0.01	0.600	0.01	3.01	0.0

Where:
Ra (pu) is the stator resistance,
Tdo' (s) is the D: unsaturated transient open T constant,
Tdo" (s) is the D: unsaturated sub-transient open T constant,
Tqo' (s) is the Q: unsaturated transient open T constant,
Tqo" (s) is the Q: unsaturated sub-transient open T constant,
H (s) is the inertia constant, and
D(pu/pu) is the synchronous mechanical damping.

APPENDIX D: Exciter Data-Part 1 (IEEE Type DC1A)

GEN	KA	TA	VRmin	VRmax	KE	TE	KF	TF
1	20.0	0.2	-5.0	5.0	1.0	0.314	0.063	0.35
2	20.0	0.2	-5.0	5.0	1.0	0.314	0.063	0.35
3	20.0	0.2	-5.0	5.0	1.0	0.314	0.063	0.35

Where:
KA is the gain,

TA is the time constant,
VRmin is the minimum controller output,
VRmax is the maximum controller output,
KE is the exciter field resistance line slope margin,
TE is the exciter time constant,
KF is the rate feedback gain, and
TF is the rate feedback time constant.

APPENDIX E: Exciter Data-Part 2 (IEEE Type DC1A)

GEN	EX1	S(EX1)	EX2	S(EX2)
1	3.3	0.6602	4.5	4.2662
2	3.3	0.6602	4.5	4.2662
3	3.3	0.6602	4.5	4.2662

Where:
EX1 is the value of E at SE1,
S(EX1) is the value of SE at E1,
EX2 is the value of E at SE2, and
S(EX2) is the value of SE at E2.

APPENDIX F: Governor Data (TGOV1)

GEN	R	T1	Vmax	Vmin	T2	T3	Dt
1	0.05	0.05	5.00	-5.00	2.1	7.0	0.0
2	0.05	0.05	5.00	-5.00	2.1	7.0	0.0
3	0.05	0.05	5.00	-5.00	2.1	7.0	0.0

Where:
R is the permanent droop,
T1 is the governor time constant,
Vmax is the maximum value position,
Vmin is the minimum value position,
T2 is the time constant of a high-pressure fraction,
T3 is the reheater time constant, and
Dt is the turbine damping coefficient.

APPENDIX G: Transmission Line Data

Line number	R (pu)	X (pu)	B (pu)
Line 1	0.0100	0.0850	0.1760
Line 2	0.0170	0.0920	0.1580
Line 3	0.0320	0.1610	0.3060
Line 4	0.0390	0.1700	0.3580
Line 5	0.0085	0.0720	0.1490
Line 6	0.0119	0.1008	0.2090

Appendices H, I & J provide the wind plant data as follows:

APPENDIX H: **4 MW, 4000 V, 50 Hz SCIG parameters part 1**

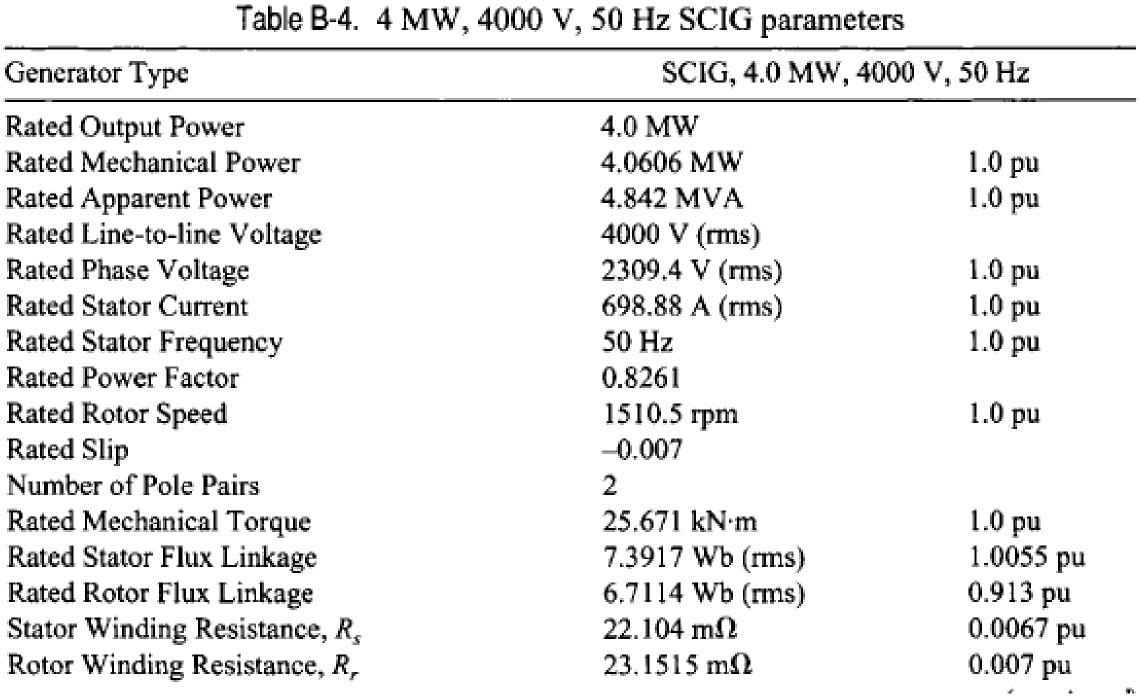


Table B-4. 4 MW, 4000 V, 50 Hz SCIG parameters

Generator Type	SCIG, 4.0 MW, 4000 V, 50 Hz	
Rated Output Power	4.0 MW	
Rated Mechanical Power	4.0606 MW	1.0 pu
Rated Apparent Power	4.842 MVA	1.0 pu
Rated Line-to-line Voltage	4000 V (rms)	
Rated Phase Voltage	2309.4 V (rms)	1.0 pu
Rated Stator Current	698.88 A (rms)	1.0 pu
Rated Stator Frequency	50 Hz	1.0 pu
Rated Power Factor	0.8261	
Rated Rotor Speed	1510.5 rpm	1.0 pu
Rated Slip	–0.007	
Number of Pole Pairs	2	
Rated Mechanical Torque	25.671 kN·m	1.0 pu
Rated Stator Flux Linkage	7.3917 Wb (rms)	1.0055 pu
Rated Rotor Flux Linkage	6.7114 Wb (rms)	0.913 pu
Stator Winding Resistance, R_s	22.104 mΩ	0.0067 pu
Rotor Winding Resistance, R_r	23.1515 mΩ	0.007 pu

APPENDIX I: **4 MW, 4000 V, 50 Hz SCIG parameters part 2**

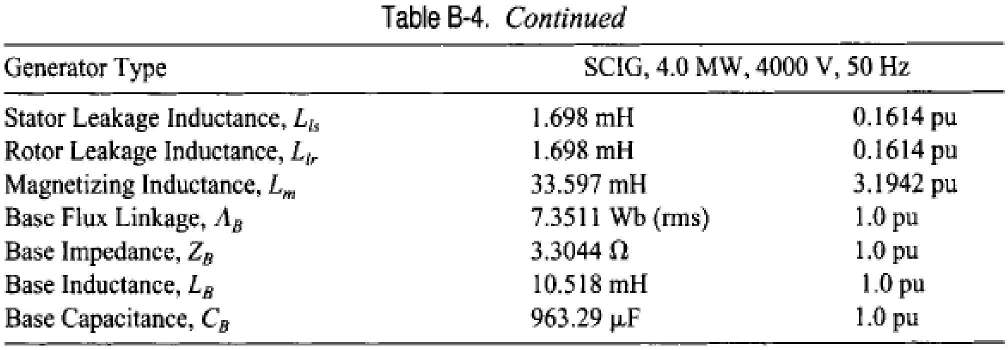
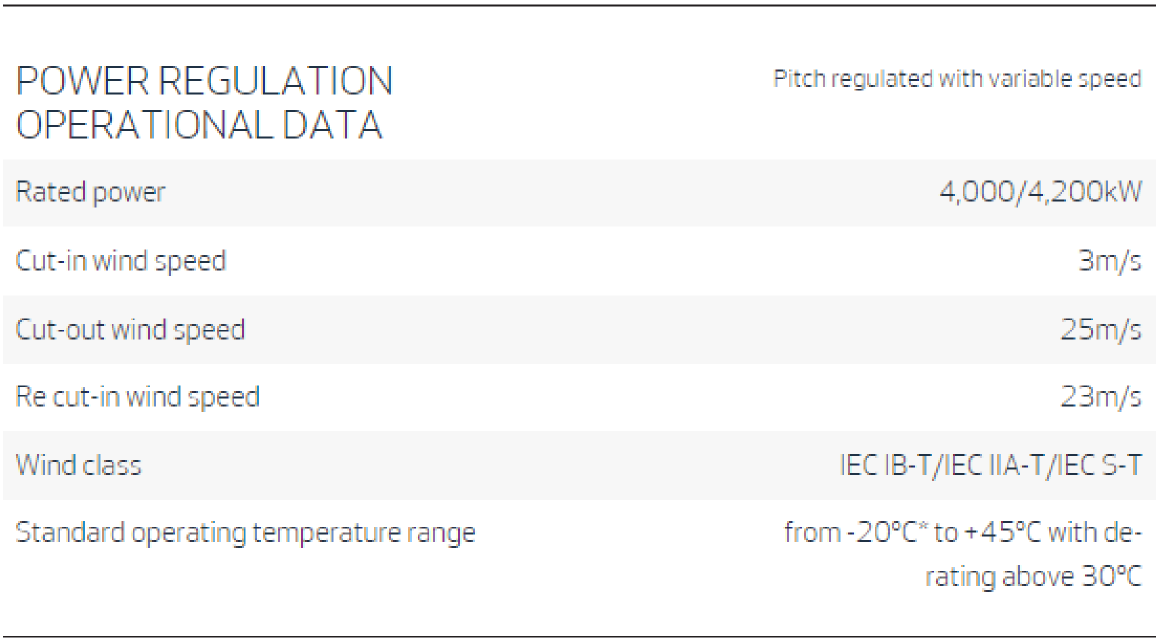


Table B-4. *Continued*

Generator Type	SCIG, 4.0 MW, 4000 V, 50 Hz	
Stator Leakage Inductance, L_{ls}	1.698 mH	0.1614 pu
Rotor Leakage Inductance, L_{lr}	1.698 mH	0.1614 pu
Magnetizing Inductance, L_m	33.597 mH	3.1942 pu
Base Flux Linkage, Λ_B	7.3511 Wb (rms)	1.0 pu
Base Impedance, Z_B	3.3044 Ω	1.0 pu
Base Inductance, L_B	10.518 mH	1.0 pu
Base Capacitance, C_B	963.29 μF	1.0 pu

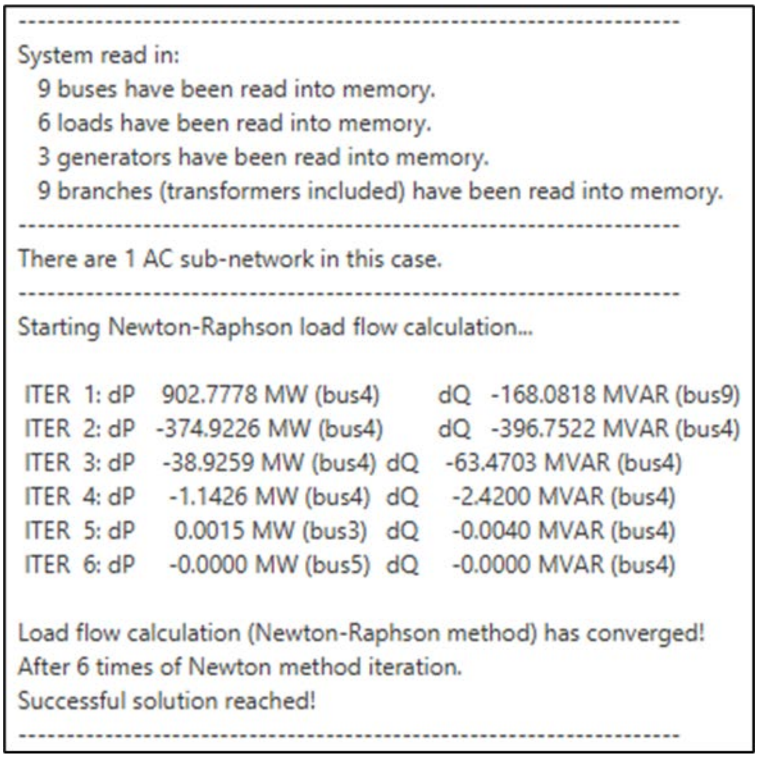
APPENDIX J: V117- 4.2MW wind turbine specifications from Vestas



POWER REGULATION	Pitch regulated with variable speed
OPERATIONAL DATA	
Rated power	4,000/4,200kW
Cut-in wind speed	3m/s
Cut-out wind speed	25m/s
Re cut-in wind speed	23m/s
Wind class	IEC IB-T/IEC IIA-T/IEC S-T
Standard operating temperature range	from -20°C* to +45°C with de-rating above 30°C

Appendices K provides the load flow computation summary as follows:

APPENDIX K: Newton-Raphson load flow output



```
--------------------------------------------------------------------
System read in:
  9 buses have been read into memory.
  6 loads have been read into memory.
  3 generators have been read into memory.
  9 branches (transformers included) have been read into memory.
--------------------------------------------------------------------
There are 1 AC sub-network in this case.
--------------------------------------------------------------------
Starting Newton-Raphson load flow calculation...

 ITER  1: dP    902.7778 MW (bus4)        dQ   -168.0818 MVAR (bus9)
 ITER  2: dP   -374.9226 MW (bus4)        dQ   -396.7522 MVAR (bus4)
 ITER  3: dP    -38.9259 MW (bus4)  dQ    -63.4703 MVAR (bus4)
 ITER  4: dP     -1.1426 MW (bus4)  dQ     -2.4200 MVAR (bus4)
 ITER  5: dP      0.0015 MW (bus3)  dQ     -0.0040 MVAR (bus4)
 ITER  6: dP     -0.0000 MW (bus5)  dQ     -0.0000 MVAR (bus4)

Load flow calculation (Newton-Raphson method) has converged!
After 6 times of Newton method iteration.
Successful solution reached!
--------------------------------------------------------------------
```