Cape Peninsula
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DEVELOPMENT OF WIND FARM INTEGRATED BATTERY ENERGY STORAGE SYSTEM TO MITIGATE THE VARIABILITY OF POWER GENERATION

by

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DECLARATION

I, Sibonelo Lucky-boy Mbanjwa, declare that the contents of this 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 opinions, not necessarily those of the Cape Peninsula University of Technology.

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ABSTRACT

Wind power generation, while a key renewable energy source, suffers from inherent variability due to fluctuating wind conditions, leading to grid instability, voltage fluctuations, and unreliable power supply. This study addresses these challenges by developing and assessing a wind farm integrated Battery Energy Storage System (BESS) at the 21 MW Chaba Wind Farm in South Africa, comprising seven 3.075 MW turbines. The integration aims to mitigate power generation fluctuations, enhance grid stability, and ensure compliance with grid codes, while accounting for economic and environmental factors to support sustainable renewable energy adoption.

Quasi-dynamic simulations were conducted using DIgSILENT PowerFactory to evaluate system performance under various scenarios, including normal operations, a 3-phase fault at cable, and a 15 MW load increase. Data was sourced from Chaba Wind Farm's operational records via SCADA (Vestas Business Online Client). The BESS control strategy involved charging during high-wind periods and discharging when output fell below a set threshold.

The BESS integration achieved up to a 30% reduction in voltage fluctuations, frequency stabilisation within 0.1 Hz, and a 50% faster fault recovery compared to non-BESS scenarios. It improved Fault Ride-Through (FRT) capabilities for double-fed induction generators and stabilised active/reactive power and current profiles. Despite limitations such as single-site focus and high initial costs, the model demonstrated cost-efficiency through energy arbitrage, validating BESS's role in enhancing power output reliability and grid resilience.

This research provides a replicable assessment for global wind-BESS integration, recommending 50-75% BESS capacity with predictive controls, while highlighting the need for policy support to address costs and battery lifespan. Future work should explore AI-driven optimisation and multi-source renewables to advance further South Africa's clean energy transition and sustainable energy infrastructure worldwide.

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DEDICATION

This thesis is dedicated to:

My late mother
Medrina Mildred Bonakele Duma

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ABBREVIATIONS/ACRONYMS

BESS	Battery Energy Storage System
BMS	Battery Management System
CAES	Compressed Air Energy Storage
CCT	Control Circuit
DC	Direct Current
DER	Distributed Energy Resources
DFIG	Double Fed Induction Generator
DS	Distribution System
EDLC	Electrochemical Double-Layer Capacitors
EMS	Energy Management System
ESS	Energy Storage Systems
FOM	Fixed Operation and Maintenance
FRT	Fault Ride-Through
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GW	Gigawatts
GWEC	Global Wind Energy Council
H_2SO_4	Sulfuric Acid
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
IRP	Integrated Resource Plan
ISGT	Innovation Smart Grid Technologies
LCA	Life-Cycle Assessment
LCOE	Levelized Cost of Energy
LMP	Locational Marginal Pricing
ML	Machine Learning
NAS	Sodium Sulphur Batteries
Ni-Cd	Nickel Cadmium
Ni-MH	Nickel-Metal Hydride
NREL	National Renewable Energy Laboratory
PCS	Power Conversion System
PCC	Point of Common Coupling
PoC	Point of Coupling
PHS	Pumped Hydro Storage

PLL	Phase-Locked Loop
PV	Photovoltaic
REC	Renewable Energy Certificate
RES	Renewable Energy Sources
RFB	Redox Flow Battery
RMS	Root Mean Square
RPP	Renewable Power Producer
ROCOF	Rate of Change of Frequency
SCADA	Supervisory Control and Data Acquisition
SMES	Superconducting Magnetic Energy Storage
SMPS	Switched-Mode Power Supply
SOC	State of Charge
SO	System Operator
SP	Set Point
TS	Transmission System
V2G	Vehicle-to-Grid
VOB	Vestas Online Business Client
VRE	Variable Renewable Energy
VRLA	Valve-Regulated Lead-Acid
WTG	Wind Turbine Generator

CHAPTER ONE

BACKGROUND OF THE THESIS

1.1. Introduction

Industrial and commercial power consumers may incorporate standby generators as localised energy sources. The generators provide a portion of the total required energy or deliver emergency power if the primary energy source fails. The utilisation of generators can be categorised into single isolated generators, multiple isolated generators, and large industrial generators (Boldea, 2017). The generators also constitute a special class of power network equipment that is very costly; therefore, the utilisation of these machines must be maximised at all costs. Energy production fluctuations are mitigated by introducing a Battery Energy Storage System (BESS) to ensure stable power is fed to the grid, enabling renewable energy (Wind Turbine Generators) to step in during an energy crisis. The development of wind farms has been rolled out to supply emission-free energy. This technology has a downside in terms of climate impact and cannot be reliable when rolled out independently; hence, the study suggests integrating BESS. Once wind velocity decreases, affecting electricity generation, the battery bank initiates discharging the necessary amount of energy to compensate for the reduced power due to the lower production rate.

The development of a wind farm integrated with a BESS aims to alleviate power generation fluctuations by employing a Control Circuit (CCT). This CCT will facilitate charging of battery banks during power production and monitor power output to the grid. If the control circuit measures a value below the set point, then the integrated BESS system will compensate by discharging to the grid. This study aims to examine the proposed integration functions, which are the Wind energy and BESS integration, and will be based on different scenarios, considering climate impact/effects, maintenance schedules, and curtailments imposed by either the environmental authorities or the buyer. Having power available during different peak times also boosts the economic need for the technology. This technology supports investors by enabling power dispatch during high-peak seasons/times, thereby enhancing economic benefits, and can also be used for peak shaving during power generation fluctuations. The study assesses the power availability advantage for integrating wind energy and BESS to mitigate these factors. This research assesses the benefits of integrating wind energy with a BESS system, accounting for peak and valley electricity prices, in terms of power generation availability. The charging and discharging strategy for the BESS is proposed to mitigate power generation variations, based on projected wind power output. The simulation will later highlight the efficiency of the model through various scenarios (Miao et al., 2021).

The research provides assurance of power availability throughout all seasons, regardless of climate change and other factors that threaten production and power availability, including maintenance intervals and fluctuating wind conditions. The study and findings of the 2019 Innovation Smart Grid Technologies (ISGT) Latin American study depict that the Double Fed Induction Generator (DFIG) is the wind turbine topology and is very vulnerable to grid disturbances. During fault conditions, it cannot sustain or mitigate the issues arising, leading to rotor overcurrent damage. The Direct Current (DC) link voltage control may exceed the allowable maximum voltage limits due to uncontrollable overvoltage, leading the protection system to deactivate the wind power plant. One of the major issues is the fluctuation of wind driving the wind turbine for power generation, causing grid stability issues. This project evaluated BESS's ability to control the output power of a DFIG and its effect on improving the DFIG's FRT capacity (Innovative Smart Grid Technologies Conference, Latin America, 2019). Korea University's School of Electrical Engineering (2021) proposes an innovative, coordinated control strategy to optimise energy utilisation and enhance the power availability of wind turbines through battery energy storage systems.

1.2. Background and Motivation

Constantly rising energy demand and increased sustainability concerns about power generation from fossil fuels are driving the integration of renewable energy sources, particularly wind power, into the current power grid. Government policies, societal movements, advancements in renewable energy technology, current installation contexts, and the research initiatives from academia and industry all indicate a power sector devoid of emissions. Due to these resolutions, a comparable rate of integration of renewable energy sources is expected to persist in the coming years (Al-Shetwi, 2022). Wind energy is unpredictable, erratic, and hard to predict. Low levels of implementation can address the variability of renewables by integrating BESSs and using existing tools to manage supply and load changes. On the other hand, additional resources are needed when renewable energy sources account for a larger share of the power supply capacity to balance erratic supply with erratic customer demand (Soares et al., 2018).

In 2023, the global renewable energy sector expanded considerably, with battery storage capacity rising 120% to 55.7 GW, largely driven by China's 250% increase, which boosted capacity from 7.8 GW in 2022 to 27.1 GW. Concurrently, the global wind sector installed a historic 117 GW of new capacity, a 50% increase from the prior year (Pontes et al., 2023; Zhao et al., 2023). This swift progress underscores the importance of combining wind energy with storage technology, especially for frequency management and for maintaining stable power system operations. The Global Wind Energy Council (GWEC) confirms 2024 as a record year, with 117 GW of new installations raising cumulative global wind capacity to 1,136 GW, and projects an additional 210 GW by 2030 (GWEC, 2024). These advancements highlight the imperative for energy storage systems to balance sporadic power generation, maintain grid stability, and reduce long-term energy costs, thereby facilitating a reliable and economical transition to renewable energy.

In terms of the subject matter of this project, adding large-scale RES of an alternating nature has increased the dynamic and transient stability issues in the current electric grid. RES has varying operational parameters and intrinsic advantages compared to traditional synchronous generators. Utility issues are a global disaster, and the world is on a journey to reduce carbon emissions by introducing renewable energy generation platforms. This has led to positive results in addressing the carbon emissions problem (Weisser, 2004). The power output is unreliable, and the grid requires corrective measures to ensure a stable power feed. Introducing BESS will stabilise the power fed to the grid, thus maximising power availability to the national grid. Maintenance and breakdown attendance will receive strong attention, with the lowest rework rates; there will also be no power loss during breakdowns or scheduled maintenance (Matthew et al., 2012). The corporate structure for energy purchase in Africa focuses on the availability of power fed into the grid. While the development of these sites follows the study of wind availability, this does not mean that wind is 100% at maximum production in all seasons. There are unforeseen cases in which the use of BESS can mitigate power losses or cuts.

The development of wind farms integrated with BESS faces significant challenges across technological, economic, political, social, and environmental dimensions as illustrated in Figure 1.1.

Figure 1.1: **Challenges of wind power** (Ullah et al., 2024)

Key technological issues include network instability, low inertia, frequency fluctuations, and limitations in current energy storage technologies, such as low energy density and a short lifespan of lithium-ion batteries. Economically, the high cost of energy storage systems and the investment required for advanced materials and technologies hinder widespread adoption. Politically, insufficient supportive policies and regulatory frameworks slow the transition to renewable energy. Socially, challenges arise from public acceptance and integration into existing societal and energy infrastructures. Environmentally, large-scale wind farm installations and the ecological impact of storage solutions pose additional concerns. Addressing these obstacles is critical to advancing wind power development and to achieving a stable, efficient, and sustainable energy transition (Ullah et al., 2024).

Energy storage technologies have the potential to reduce active power fluctuations, thereby mitigating the negative impacts of integrating large amounts of wind energy into the electrical grid. This is the main motivation and benefit behind this integration. To enhance the frequency response of wind energy fed into power grids, this study introduces droop and step-response controllers coupled with energy storage. Using a high-power-density storage system with limited energy resources yields somewhat higher step-response performance with the step-response controller than with the droop controller. The grid frequency can be supported by a BESS through efficient AC-DC converter control and regulation of the BESS's input current. The proposed controller also shows promise for enhancing the system's fault ride-through capability across a range of transitory scenarios (Alam et al., 2020).

The optimisation of renewable resources: It has been demonstrated that electrifying rural villages and urban areas with renewable energy is both practical and economical, and it also helps the region achieve its long-term development objectives. Sustainable energy systems face the challenge of capacity planning due to the intermittent and variable nature of renewable energy sources and the need to fulfil changing needs over time. Developing a cost-efficient energy system that supplies the region with reliable electricity requires an effective strategy, given the nonlinearity and nonconvexity of the energy planning problem. This study proposes a rural microgrid in a remote mountain community in India. The area's current energy resources are combined in the integrated model. The smart grid, or hybrid system, combines technologies to improve production and mitigate potential grid issues. This accounts for systems such as solar photovoltaics, micro-hydropower, wind, biomass, and storage. For microgrid modelling, the development of a renewable energy project is the starting point. The proposed integration of wind energy and BESS utilises the differential energy demand and disturbances on the PPC technique to utilise the configuration of the system, whether to charge or discharge, to examine the total operating and energy costs per unit (Kamal et al., 2023).

In summary, the gist and positive need for the deployment of wind farm integrated BESS revolve around the need to; address the fluctuation of wind power generation, promote grid stability and reliability, eliminating the dependence to burning of carbon fuels to generate power, and supports the environmental and economic goals. These factors combined drives research, innovation, and investment in the field to make renewable energy source more dependable and sustainable power source.

1.3. Statement of the Research Problem

The regular nature of wind power generation poses massive challenges to maintaining a stable and reliable grid supply (Wohland et al., 2019). Besides advancements in grid-level integration and a forecasting strategy, there are limitations in fully addressing the variability observed in wind power. The research notes the critical need for an on-site storage solution to mitigate the effects of intermittency, thereby supporting the proposal to develop a wind farm-integrated BESS. With only wind as a power source, grid-level integration faces significant constraints in efficiently storing and delivering wind-generated energy due to the unpredictability of wind patterns and their variability (Ciupăgeanu et al., 2019). Sophisticated forecasting methods, while beneficial, cannot eliminate variability, and unexpected fluctuations can still impact grid stability (Wohland et al., 2019). This research identified the gap in current solutions to mitigate these variabilities. It assesses the need to explore on-site storage as a more direct and effective approach to address the challenges associated with wind power intermittency and support the wind farm. The proposal for a wind farm integrated with a BESS aligns with the growing recognition of the role of energy storage systems in enhancing the reliability of renewable energy sources (Bessa et al., 2019). Integrating BESS directly into the wind farm infrastructure will promote compliance with environmental principles and grid code requirements. The research aimed to create a solution that would capture excess energy to recharge batteries during peak wind conditions and provide a stable, consistent energy output during periods of low wind by discharging to the grid.

This study addressed intermittency and the mismatch between wind energy production and energy consumption by proposing a localised storage system capable of retaining excess energy during high wind conditions and discharging it during low wind conditions, thereby stabilising the grid and mitigating fluctuations (Bessa et al., 2019). A wind farm integrated with BESSs' prospective advantages include enhanced grid stability, increased reliability, and the capacity to deliver a continuous power supply to consumers, thus fostering a more reliable and resilient energy infrastructure (Ciupăgeanu et al., 2019). The problem statement highlights the poor quality of existing solutions for completely resolving the intermittency of wind power generation. The research supports the development of a wind farm-integrated BESS to address the shortcomings posed by wind power variability through a more direct, on-site storage technique. This aligns with the overarching objective of improving the reliability and sustainability of renewable energy sources amid evolving energy demands and environmental factors.

1.4. Research Aim and Objectives

Aim

This research aimed to develop and evaluate the optimisation of a wind farm-integrated BESS to mitigate the variability of wind power generation fed to the grid, improve grid stability, and maximise the reliability and sustainability of the power supplied to the grid.

Objectives

- To examine the stability of power variations in South Africa: Investigate the existing grid challenges in maintaining a stable power supply due to renewable energy variability and its implications for the national grid due to various factors.

- To assess the performance of the proposed wind farm integrated BESS: Conduct simulation and modelling techniques to assess BESS's ability to address the intermittency of wind energy and its impact on grid stability and reliability issues.
- To identify solutions to mitigate faults and instabilities in the wind power systems:
- To enhance wind farms' Fault Ride-Through (FRT) capabilities by integrating BESS and advanced control techniques.
- To assess the scalability and applicability of the proposed technology: Assess how the integrated system can be adopted for other wind farms, by ensuring its deployment to broader renewable energy goals.

1.5. Significance of the Study

This study is crucial as it challenges the factors of grid instability and power generation variability resulting from the characteristics of renewable energy sources, especially wind power, by developing an optimised wind farm integrated with a BESS. The research improves grid stability, ensures a high-quality, stable supply to consumers, enhances FRT capabilities, and ensures a consistent and reliable power supply by mitigating fluctuations from wind sources. Integrating BESS with renewable energy sources immediately addresses power deficiencies by accumulating excess energy during periods of high wind and releasing it during periods of low wind. This promotes the widespread adoption of renewable energy in South Africa, integrated with energy storage technologies, aiding the shift to cleaner energy sources while reducing dependence on fossil fuels and greenhouse gas emissions. The research assessed the economic and environmental viability of integrating BESS, proposing a scalable model with an optimised storage capacity of 50-75% of the wind farm's peak output to ensure cost-efficient, sustainable energy solutions. The research examined the scalability and adaptability of the proposed model for replication in other wind farms, thus promoting a robust renewable energy infrastructure. The study utilised advanced simulations and control strategies to foster technological innovation and provide actionable insights for policymakers and stakeholders, thereby aiding long-term sustainability objectives.

1.6. Research Methodology and Scope

For this research, a literature review outlines the data-collection method and the simulation of plant behaviour regarding storage and discharge rates for wind energy and BESS. The experimental method was used for data collection and analysis. The research focused on developing a wind farm with BESS to mitigate power generation variability caused by natural weather conditions and technical issues affecting power output. The data were extracted from Vestas Online Business Client (VOB), and the analysis and comparison were conducted between projected and actual production to determine storage capacity for annual, monthly, and daily production. Using the DigSILENT PowerFactory simulation tool, the research findings from the simulation experiment were provided with concrete evidence. BESS was utilised to address this matter, and the battery size was calculated. Factors such as quality storage and safety features were considered when selecting a storage platform. The schematic diagram outlined below was employed to accomplish the study objectives:

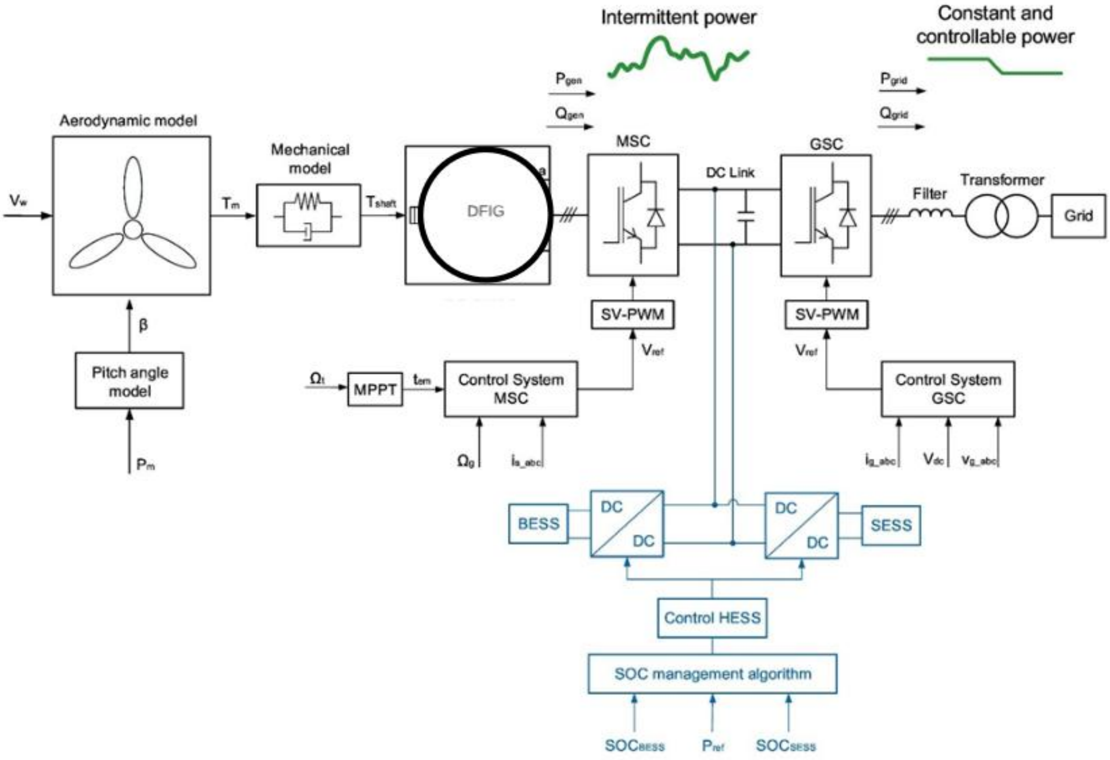


Figure 1.2: **Outline of the wind farm with BESS** (Pinazo & Martinez, 2022)

Figure 1.2 is an illustration of a schematic diagram of a wind power system that uses BESS. The four parts that make up the system in question are: a model of the wind turbine, a model of wind speed production, a model of the battery, and a model of BESS control. At the outset, wind speed is constructed from a composite model comprising four components. Analysing the produced wind speed and the characteristic wind power curve allows one to then calculate the maximum available wind power. As a third step, the wind speed and its characteristic power-speed curve are used to configure BESS capacity. After that, the researcher proposes a control strategy aligned with the power reference. Lastly, the viability of the proposed methodology is demonstrated through a series of simulations.

1.7. Delineation of the Study

This study focused on the integration of BESS with wind farms to mitigate the variability of wind power generation and enhance grid stability. The scope was confined to analysing the performance of a wind farm-integrated BESS using data collected from the Chaba Wind Farm in the Eastern Cape of South Africa. The research employed simulation and modelling techniques to evaluate the system's effectiveness in addressing power generation intermittency, thereby enhancing FRT capabilities and ensuring a reliable energy supply. The key limitations included the exclusive focus on wind energy as the renewable energy source and the application of BESS for grid-scale storage. The study did not consider other renewable energy sources or alternative storage technologies. Moreover, the research was bound by the availability of historical wind data and the operational constraints specific to the Chaba Wind Farm. While the findings aim to provide scalable insights, their applicability may vary across regions and wind farms due to geographical, technical, and economic factors.

1.8. Overview of the Study’s Structure

This research is structured into six chapters, each addressing a specific aspect of developing and evaluating a wind farm integrated BESS to mitigate power generation variability and enhance grid stability.

Chapter One: Introduction

The introduction outlines the challenges posed by the variability and intermittency of wind power generation, emphasising the need for integrating BESS to stabilise the grid and ensure a reliable power supply. It lays the foundation by presenting the research aim and objectives, while highlighting the study's significance in addressing renewable energy challenges and supporting South Africa’s transition to sustainable energy systems.

Chapter Two: Literature Review

This chapter reviews existing studies on wind energy systems and BESS technologies, focusing on the advancements in energy storage integration, FRT capabilities, and grid stabilisation strategies. It explores gaps in current knowledge, including economic and environmental considerations, and positions this research as a novel contribution to enhancing the scalability and reliability of renewable energy systems.

Chapter Three: Methodology

The methodology chapter provides a detailed account of the research approach, combining qualitative and quantitative methods. It explains the integration of wind farms and BESS models, the data-collection strategies at the Chaba Wind Farm, and the use of simulation tools such as DIgSILENT PowerFactory. The chapter also discusses technical parameters, including wind farm equipment, BESS sizing, and the grid compliance requirements. It also describes the experimental setup for validating the system's performance under various scenarios.

Chapter Four: System Development, Results, and Discussion

This chapter presents the development of the wind farm-integrated BESS model, detailing the control strategies and optimisation techniques employed to mitigate power fluctuations. It includes the results of simulations evaluating system performance under different conditions, such as wind-speed variability and fault scenarios. The chapter also interprets the findings, discussing the system's effectiveness in stabilising the grid, enhancing economic feasibility, and supporting renewable energy adoption. The challenges, limitations, and comparisons with existing literature are highlighted to contextualise the outcomes.

Chapter Five: Quasi-Dynamic Simulations

Chapter five analyses the performance of the wind farm with and without BESS using the quasi-dynamic simulations in DIgSILENT PowerFactory. It evaluates voltage, frequency, active power, reactive power, and current under normal operations, fault conditions, and load variations at the Chaba Wind Farm. The results highlight BESS's critical role in mitigating variability, improving fault recovery, ensuring grid stability, and providing insights into its practical benefits for renewable energy systems.

Chapter Six: Conclusion and Recommendations

The final chapter summarises the key findings, emphasising the effectiveness of the integrated BESS in addressing wind power variability and enhancing grid reliability. It offers actionable recommendations for stakeholders and policymakers to facilitate the deployment of similar systems and highlights broader implications for renewable energy scalability. The suggestions for future research include advancing battery technologies, conducting extended case studies, and deploying the system in real-world settings to further refine and validate the proposed system.

1.9. Summary

Chapter one established the foundation for this research by highlighting the critical challenges associated with the variability and intermittency of wind power generation. It emphasised the importance of integrating BESS with wind farms to address these issues and ensure grid stability, reliability, and consistency in power supply. The chapter outlined the research aim, which focused on developing and evaluating an optimised wind farm-integrated BESS, and detailed the objectives guiding this study. Additionally, the chapter underscored the significance of this research in advancing South Africa's renewable energy goals, reducing reliance on fossil fuels, and promoting sustainability. By addressing these challenges, this study aimed to offer a scalable and economically viable solution for integrating renewable energy into the grid, setting the stage for subsequent chapters to explore the existing literature on the impact of wind farm BESS globally.

CHAPTER TWO

LITERATURE REVIEW

1.10. 2.1. Introduction

The literature review provides a comprehensive understanding of the background and context of integrating BESS with wind farms. It explores the challenges associated with wind power variability, highlights the role of BESS in mitigating them, and identifies gaps in existing research, thereby setting the stage for the study on developing a wind farm-integrated BESS.

This literature review considers several research articles, including journal articles, standard documents, textbooks, and wind farm operating manuals. The variation is widespread due to several effects, such as wind speed variability and regional wind power fluctuations affecting grid stability as well as the availability of the generated power to be consumed by the customers. Several issues were discovered, and several mitigation rooms were available to support the research. One wind farm was selected as a reference point for data collection and modifications to accommodate BESS use. The literature review examined power variability in the renewable energy environment for power utilities.

2.2. Background and Context of Wind Farm and Battery Energy Storage System

2.2.1. Wind Farm

Wind farms, defined as wind turbines installed on land to convert wind energy into electricity, are a cornerstone of renewable energy strategies (Haces-Fernandez et al., 2022). Wind energy generation technology is classified as offshore or onshore. Offshore wind is in water, and onshore wind is inland (Richards, 2013). Onshore wind farms are a mature, cost-effective, reliable renewable energy source, but noise complaints and obstructions limit wind potential (Haces-Fernandez et al., 2022; Diógenes et al., 2020). In contrast, offshore wind farms in bodies of water have stronger winds and greater energy potential. Technology is less mature, and the implementation costs are higher (Wu et al., 2014). This study focused on an onshore wind farm; Figure 2.1 depicts one.

Figure 2.1: **Onshore wind farm (NZ Herald, 2019)**

The primary characteristics of these farms include the location (typically in areas with consistent wind patterns), size, and capacity, which have evolved significantly over time due to technological advancements. Each turbine's height, rotor diameter, and the overall layout of the farm are crucial for optimising wind energy capture (Desalegn et al., 2023; McKenna et al., 2022; Gwabavu et al., 2023). The functions of onshore wind farms extend beyond electricity generation, as they play a pivotal role in reducing carbon emissions, fostering energy independence, and contributing to sustainable development. Government policies, environmental considerations, and community engagement are integral to the development and operation of these farms (Wu et al., 2020; Angelo, 2020). Moreover, modern onshore wind farms incorporate sophisticated Energy Management Systems (EMS) and predictive maintenance techniques to enhance efficiency and reliability. However, challenges such as social acceptance, environmental impact on local wildlife, and decommissioning old turbines are ongoing concerns. The future of onshore wind energy focuses on integrating large-scale storage solutions and grid synchronisation to manage the intermittent nature of wind power, ensuring a stable and sustainable energy supply (Desalegn et al., 2023; Farkat Diógenes et al., 2020). Figure 2.2 shows the trend of increasing wind turbine size over recent years, driven by the need to enhance efficiency and reduce costs.

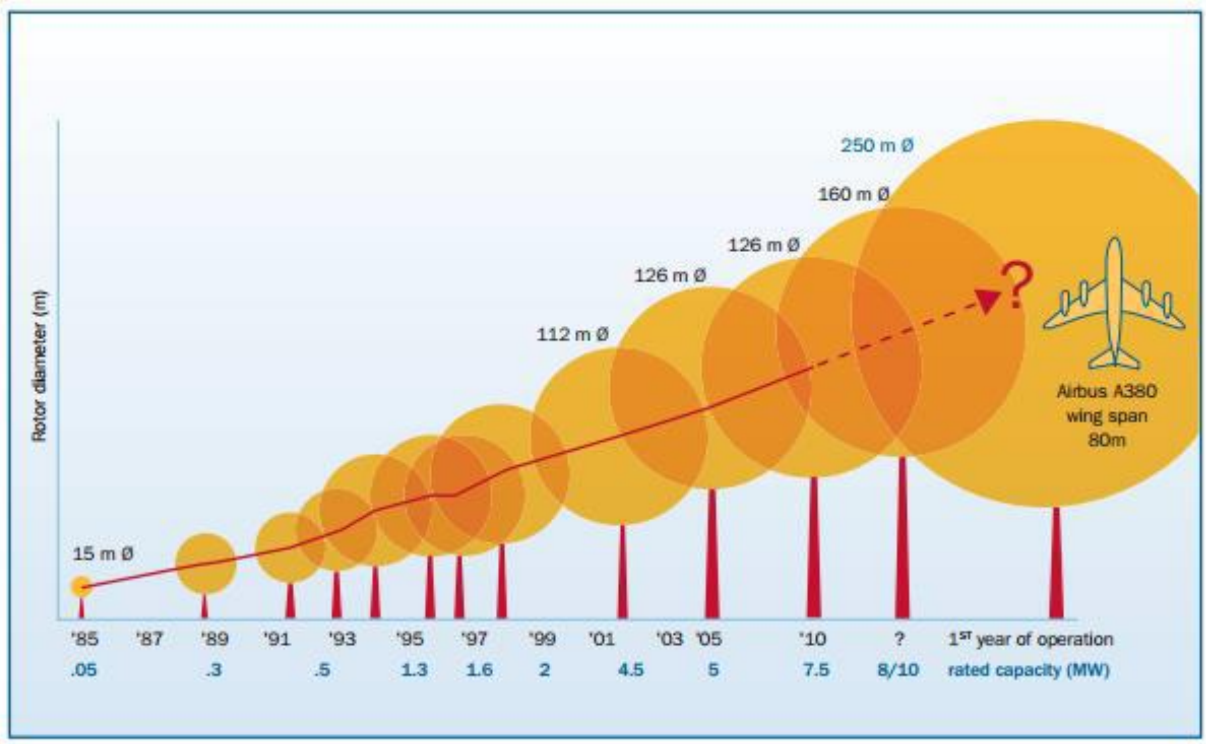


Figure 2.2: **Scaling up of wind turbines** (Fichaux et al., 2011)

The improvements in wind turbine technology, including larger turbine dimensions and enhanced capacity, require advanced control systems to address the escalating issues of wind energy utilisation (Fichaux et al., 2011). Conventional independent turbine control, aimed at optimising individual outputs, is proving insufficient due to aerodynamic interactions and the growing demand for flexible, centralised management in extensive wind farms. Regulating the aggregate power output of clustered turbines requires sophisticated control systems to address grid integration challenges, especially with variable wind energy. The turbines must rapidly and adaptively modify the power production under fluctuating conditions to provide steady and secure operation akin to traditional power plants (Fichaux et al., 2011). This dissertation presents a wind farm architecture featuring a central controller that orchestrates turbine operations, offering adaptable power-control capabilities and addressing critical challenges in integrating wind power into the grid.

2.2.2. Battery Energy Storage Systems

The power system network increasingly incorporates renewable energy sources, particularly wind power. This has led many people to express grave concerns about the reliability and quality of the power system. One recommendation to improve the efficiency and reliability of power systems is to incorporate energy storage devices into their networks (Bayindir et al., 2016). Furthermore, the wind farm owners may increase the profit margins and even engage in arbitrage in the deregulated markets by using these storage devices. Machines, electromagnetic fields, chemicals, heat, and electrochemical systems are all viable options for storing energy (Zhao et al., 2015). These Energy Storage Systems (ESSs) are presented below.

i. Mechanical energy storage

Mechanical energy storage systems, such as Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), and flywheels, use automated means to store energy (Grazzini & Milazzo, 2008; Zhao et al., 2015).

a. Pumped hydro storage: The PHS systems generate electricity by pushing water uphill and releasing it later to generate power. The systems are the most popular large-scale energy storage technology, with enormous power capacity, long cycle life, and an affordable price per stored energy unit. However, a lack of suitable places and environmental issues limits their distribution (Zhu & Ma, 2019).
b. Compressed air energy storage: The CAES systems create electricity by compressing air and releasing it through a turbine to generate power. They provide a lot of electricity, a long cycle life, and minimal environmental impact. However, the system's energy density, round-trip efficiency, and requirement for certain geological formations prevent extensive deployment (Feng & Yu, 2022).
c. Flywheel energy storage: Flywheels are devices that use rotating kinetic energy to store energy. A flywheel is a revolving mass that spins rapidly to store energy. It is commonly a disk or cylinder. When power is required, a generator transforms the flywheel's rotating energy into electrical energy (Saha et al., 2022). Flywheel systems are ideal for applications that require quick responses and short-term energy storage.

Figure 2.3 shows how EES are classified. Some of the other ESSs are depicted in Figure 2.4, respectively.

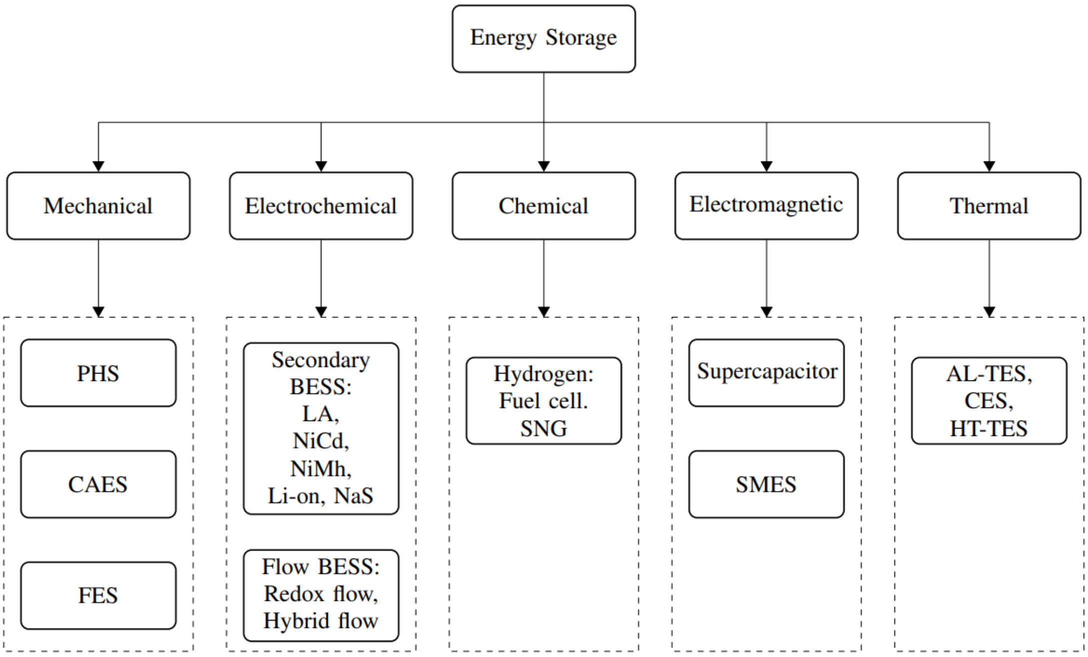


Figure 2.3: **Classification of energy storage systems** (Zhao et al., 2015)

ii. Electrochemical energy storage

Reversible electrochemical reactions store energy in electrochemical storage systems such as batteries. Among these systems are:

a. Lead-acid batteries: The oldest and most recognised electrochemical storage technology is lead-acid batteries, which are known for their low cost, excellent reliability, and well-developed recycling infrastructure. They have a poor energy density, short cycle life, and low round-trip efficiency (Divya & Østergaard, 2009).
b. Lithium-ion batteries: A lithium-ion battery has a high energy density, a long cycle life, and a high efficiency for round-trip travel. Despite their higher cost than lead-acid batteries, they have become the dominant technology for electric vehicles and stationary energy storage applications (Kim et al., 2019).
c. Sodium Sulphur Batteries (NAS): The NAS batteries are suitable for large-scale energy storage on the grid due to their superior energy density, extended lifecycle, and remarkable round-trip efficiency. However, elevated operating temperatures and limited resource availability limit their applicability (Kalair et al., 2021; Divya & Østergaard, 2009).
d. Flow batteries: Scalability, a long cycle life, and a low self-discharge rate are characteristics of flow batteries, which store energy in the form of liquid electrolytes. However, poor energy density and intricate system architecture restrict the usefulness (Soloveichik, 2015).

e. Chemical energy storage: This systems stores chemical energy which can be converted to electrical energy, some of these chemical reactions are hydrogen or synthetic hydrocarbons. They can provide long-term storage and high energy density but face challenges regarding round-trip efficiency and infrastructure requirements (Schmidt-Rohr, 2018).

iii. Electromagnetic energy storage

High-power, and short-duration applications can benefit from electromagnetic energy storage systems because they store energy in electric or magnetic fields and discharge it quickly (Castro-Gutiérrez et al., 2020). The two main types of electromagnetic energy storage systems are Superconducting Magnetic Energy Storage (SMES) and supercapacitors.

a. Supercapacitor: The electrostatic double-layer that forms at the interface between an electrode and an electrolyte is what stores energy in supercapacitors, often referred to as the ultracapacitors or Electrochemical Double-Layer Capacitors (EDLCs). Instead of batteries, the supercapacitors store energy through chemical processes in an electric field (Castro-Gutiérrez et al., 2020). Applications that require high power and rapid charge-discharge cycles are ideally suited to supercapacitors.
b. Superconducting Magnetic Energy Storage (SMES): The SMES devices use the magnetic field produced when direct current passes through a superconducting coil to store energy. The coil is cooled to very low temperatures, typically liquid helium or nitrogen, to achieve a superconducting state with zero electrical resistance (Breeze, 2018). SMES are suitable for various applications that require rapid response times and high power.

iv. Thermal energy storage

Water, molten salts, or phase-change chemicals are some of the substances used in thermal energy storage devices to store heat or cold. When needed, they may release the excess energy stored in them, whether it's from renewable sources or industrial waste heat (Zinurov et al., 2020). The bar chart in Figure 2.4 illustrates the technical maturity of various types of ESSs:

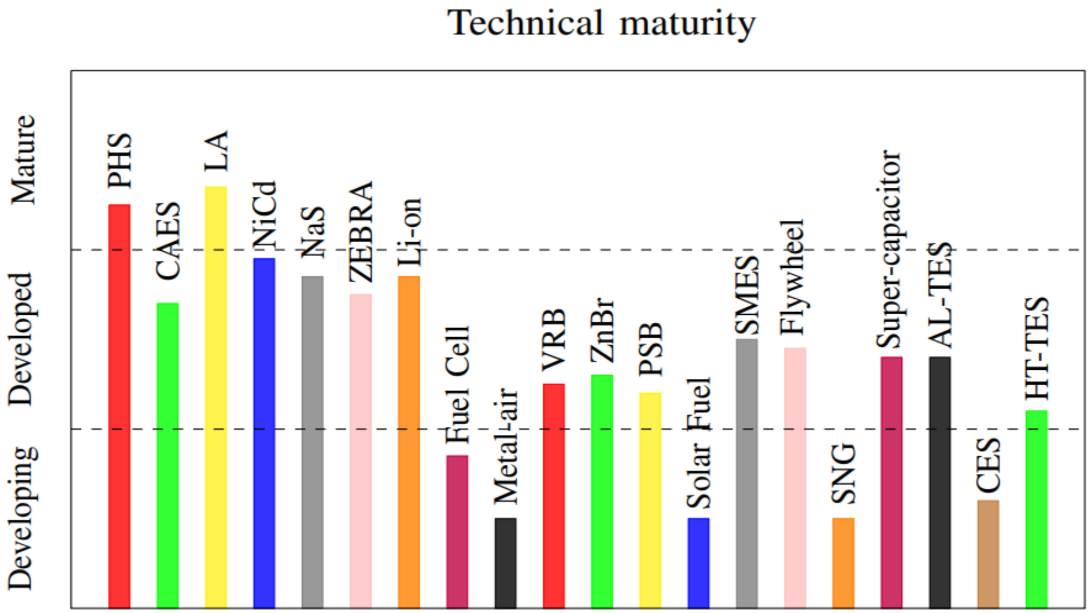


Figure 2.4: **Energy storage systems maturity** (Zhao et al., 2015)

Depending on the required storage capacity, discharge length, and power output, each energy storage technology has specific properties and is suited for applications. To address the challenges of the increased integration of renewable energy sources, a thorough understanding of these technologies is essential to guide the selection and deployment of suitable storage systems.

This study focused on BESS. Figure 2.5 illustrates the components and systems of BESS, along with their linkages. The units are categorised into various BESS component areas. The distinct component categories include battery, system operation, power electronics, and grid connection. This is a general configuration of the BESS, which may vary from case to case.

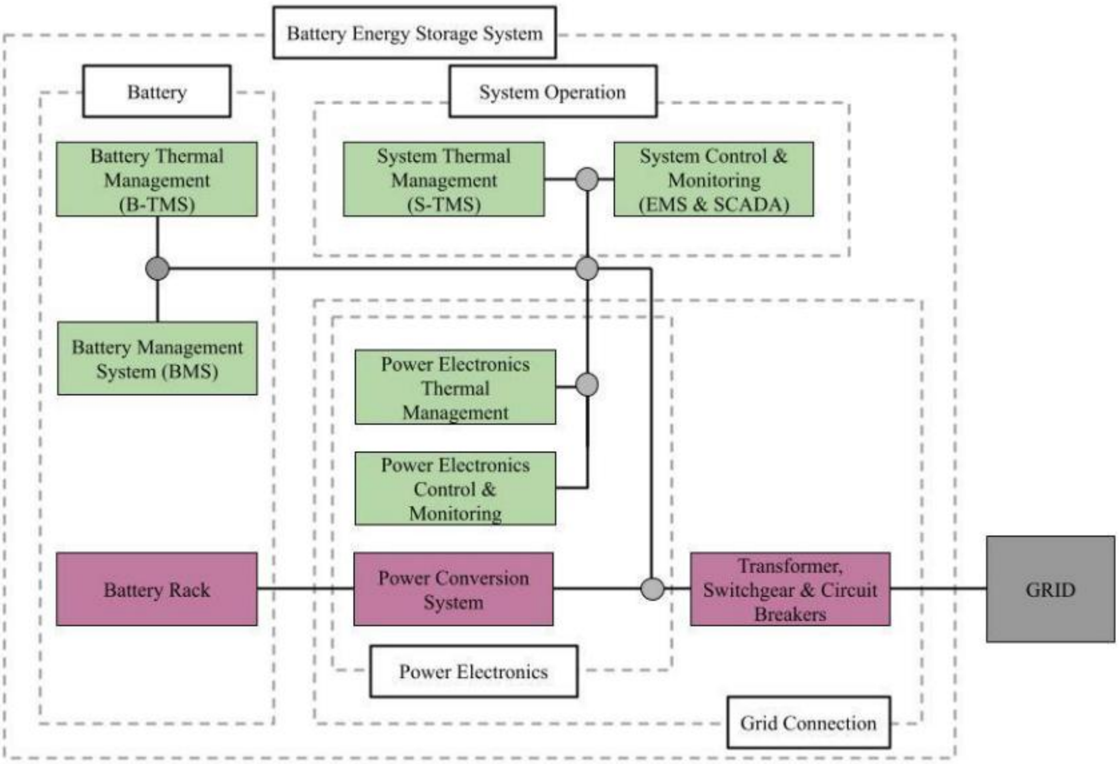


Figure 2.5: **Schematic configuration of BESS** (Hesse et al., 2017)

The research study concludes by offering a plausible outlook for battery technology integration with wind farm for grid connection (Divya & Østergaard, 2009).

2.2.3. Grid Integration

The integration of wind power into power systems signifies a turning point in the transition to renewable energy. Bessa et al. (2019) notes that wind farms are becoming more important in the fight against climate change and the increasing number of worldwide efforts to reduce the use of fossil fuels. Wind power's unpredictable nature poses a challenge to grid stability, necessitating creative approaches to reliable integration (Nomandela et al., 2023a).

According to Bessa et al. (2019), adaptive technologies are needed to make wind energy more reliable, and the importance of controlling wind power variability is increasing. Given this situation, BESS becomes a practical option. Adaptive systems are required to store excess energy during high-generating intervals and discharge it during low-wind conditions due to the fluctuating nature of wind power, characterised by changes in wind speed and direction (Ciupăgeanu et al., 2019).

The integration of BESS with wind farms mitigates variability issues, enhancing the consistency and stability of power output. Ciupăgeanu et al. (2019) underscore the significance of BESS in mitigating power fluctuations, improving grid stability, and facilitating the efficient integration of wind-generated electricity. Integrated systems have the capacity to transform the renewable energy sector, providing a dependable and scalable approach to addressing the variability of wind power.

Watson (2019) elucidates the practical applications of BESS in mitigating wind power variability, emphasising the need to account for specific contextual factors in the implementation of integrated systems. The study underscores the need for flexible, tailored solutions to accommodate the distinct attributes of various wind farms and their respective environments. This corresponds with the research's emphasis on creating a wind farm-integrated battery energy storage system customised for the conditions and needs of the selected study area.

Wind power, a crucial element of global sustainable energy portfolios, offers the potential to reduce greenhouse gas emissions and diversify the energy mix (Bessa et al., 2019). The increasing utilisation of wind energy highlights its significance in meeting renewable energy objectives and tackling climate change issues (Ueckerdt et al., 2015). Nonetheless, the intermittent and variable nature of wind power generation complicates its smooth integration into current power grids, requiring a sophisticated understanding of these challenges. Figure 2.6 shows the design of a grid-integrated wind farm with a BESS, as depicted by Gwabavu and Raji (2021). A wind farm, a BESS, a converter, a PMU, and a transmission line establish the system's connection to the main grid.

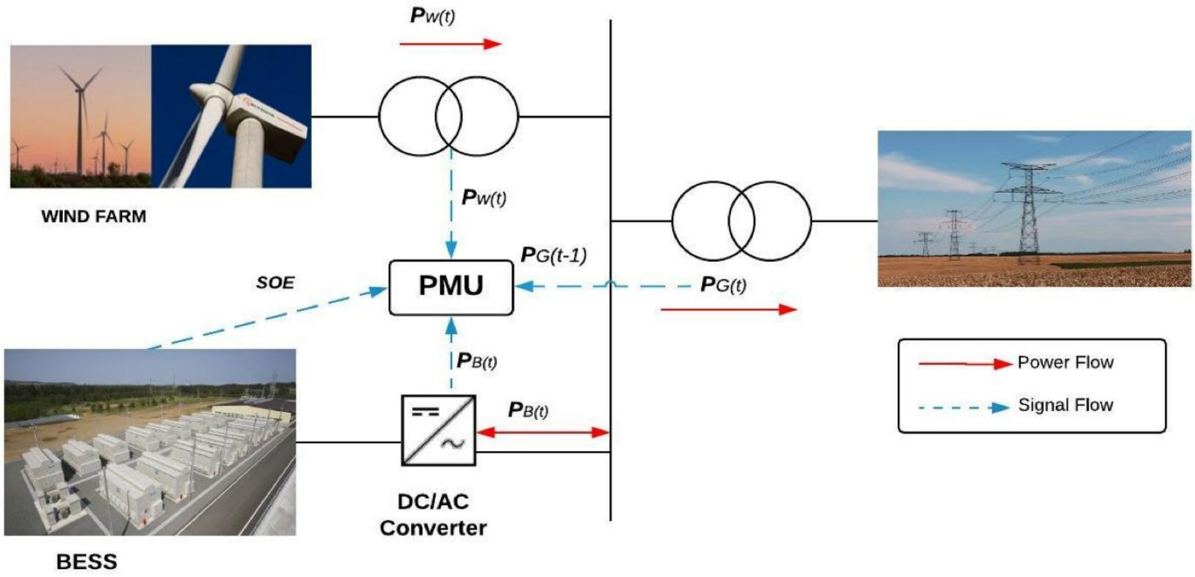


Figure 2.6: Grid-integrated wind farm with BESS (Gwabavu & Raji, 2021)

Both Bessa et al. (2019) and Ueckerdt et al. (2015) stress the need to resolve the problems caused by wind power's unpredictability. Wind energy's intermittent nature becomes more problematic for system stability as its penetration grows. Bessa et al. (2019) notes that power supply dependability is a concern due to grid instability caused by unanticipated fluctuations in wind speed and direction. As wind power continues to grow in the energy mix, the urgency of finding effective solutions is growing (Ueckerdt et al., 2015).

Voltage fluctuations and the demand for backup power represent additional challenges associated with wind power variability (Lu et al., 2018). The studies by Ciupăgeanu et al. (2019) and Watson (2019) emphasise the significance of addressing these challenges for stable grid operation. Wind power's intermittent nature calls for creative solutions, and BESS is stepping up to the plate to help with that. BESS enables the storage of surplus energy during times of strong wind generation and its subsequent release during periods of low wind, resulting in a more steady and constant power output (Ciupăgeanu et al., 2019; Watson, 2019).

Despite the valuable insights that the existing studies provide, there remains a research gap in developing practical and context-specific solutions to wind power variability. This study influenced by the works of Bessa et al. (2019); Ueckerdt et al. (2015) and Ciupăgeanu et al. (2019), aimed to contribute to this gap by focusing on the development of a wind farm integrated BESS. This approach addressed the unique challenges of wind power variability, ensuring a more reliable and stable integration into power grids.

2.2.4. Overview of Wind Energy and Challenges in Power Generation Variability

To diversify the energy mix and decrease emissions of greenhouse gases, wind power—which is a big part of renewable energy portfolios around the world—is essential (Bessa et al., 2019). Wind power is a major player in the sustainable energy sector, with an installed capacity of 743 GW by 2020 (IRENA, 2021). The intrinsic variability of wind power generation, however, makes its integration into the power grid more difficult (Ueckerdt et al., 2015).

Consistent and dependable power generation is hindered by the intermittent nature of wind, characterised by changes in wind speed and direction. This, in turn, affects the stability of the grid and overall reliability (Bessa et al., 2019; Ueckerdt et al., 2015). Power output can fluctuate when wind conditions change abruptly, since wind turbines operate best within specific speed ranges. Reliable integration of wind-generated electricity is crucial due to the challenges it poses for load balancing and system stability.

Grid instability, including the need to monitor voltage swings and provide backup power, becomes more apparent as wind energy penetration increases (Lu et al., 2018). Wind power variability is a serious problem, and these obstacles highlight the need for creative solutions. There needs to be a comprehensive solution to address the intermittent nature of renewable energy sources, such as wind power, to integrate them into current systems.

Deploying energy storage devices, especially BESS, has been highlighted as a critical solution in the literature. According to Ciupăgeanu et al. (2019) and Watson (2019), BESS enables the storage of surplus energy during periods of high wind generation and its release during periods of low wind, resulting in a steadier, more consistent power output. This aligns with the planned study's emphasis on creating a BESS adapted to reduce wind power unpredictability, adding to the ongoing discussion of efficient ways to incorporate renewable energy sources.

Ciupăgeanu et al. (2019), Bessa et al. (2019), and Ueckerdt et al. (2015) are only a few of the existing research that shed light on the ever-changing behaviour of wind farms and highlight the significance of tackling the problems linked to wind power fluctuation. By providing basic information on the intricacies of wind power integration, these studies laid the groundwork for this research.

2.3. Wind Energy and Variability

Sustainable and low-carbon power generation is a global priority, and renewable energy, especially wind energy, is playing a key role in this effort (Bessa et al., 2019; Zhang et al., 2013). Wind power is a prominent renewable energy source that can significantly reduce greenhouse gas emissions and promote environmental sustainability (Bessa et al., 2019; Valentine, 2011).

Among the many advantages of wind energy that Zhang et al. (2013) highlight are its potential to reduce environmental impact and provide reliable energy. In line with the overarching objective of developing energy systems that are resilient and adaptive, wind power helps diversify power generation away from traditional fossil fuels (Bessa et al., 2019; Zhang et al., 2013).

A comprehensive investigation of this ever-changing area is necessary, however, because power grid reliability is compromised by the intrinsic unpredictability of wind power generation (Ueckerdt et al., 2015). A thorough comprehension of the complexities of wind power variability is crucial for its efficient integration into energy systems, as demonstrated by the research of Valentine (2011) and Vargas et al. (2019). The intermittent nature of wind energy necessitates adaptive grid management solutions, as pointed out by Valentine (2011). This necessitates not only technological developments in wind turbine design (Zhang et al., 2013), but also advanced grid management approaches (Valentine, 2011; Vargas et al., 2019) that can adapt to variations in wind power.

The importance of new legislative frameworks and technological advancements in overcoming the difficulties caused by wind power generation's unpredictability is highlighted by Pryor et al. (2020). To fully utilise wind energy and ensure grid stability, the authors argue that a comprehensive strategy is necessary, encompassing technological developments, governmental interventions, and grid management plans. (Zhang et al., 2013; Pryor et al., 2020).

2.3.1. Wind Energy Technology

One important and rapidly growing part of the renewable energy scene is wind power, which is defined as the conversion of wind kinetic energy into electrical power by means of wind turbines (Ueckerdt et al., 2015). A clean, viable, and sustainable energy supply, wind power is becoming more popular around the world (Bessa et al., 2019). This in-depth analysis examines wind energy, shedding light on its environmental impact, technical developments, and the worldwide trajectory towards mainstream incorporation into energy systems.

According to Bessa et al. (2019), wind energy is particularly important for the environment because it helps slow global warming and reduces reliance on fossil fuels. According to Bessa et al. (2019), wind power aligns with worldwide initiatives to transition to sustainable, low-carbon energy sources because it significantly reduces greenhouse gas emissions. In addition to increasing energy security and diversifying power-generating sources, the decentralised nature of wind power, typically captured by wind farms, enhances its environmental attractiveness (Bessa et al., 2019; Zhang et al., 2013).

Modern wind energy systems owe much to technological developments. Wind turbine design is an area that is constantly evolving, with new advancements in efficiency, capacity, and environmental adaptability being highlighted by Zhang et al. (2013). Improvements in wind turbine technology have two main effects: first, they improve overall wind farm performance, and second, they make wind energy more competitive and affordable compared to other energy sources. (Zhang et al., 2013; Valentine, 2011).

Valentine (2011) emphasises the economic viability of wind energy, noting that ongoing technological advancements are driving cost reductions, making wind power increasingly attractive from a financial standpoint. The decreasing costs of wind energy production further propel its adoption, fostering a positive feedback loop that drives continuous research and development efforts (Valentine, 2011; Bessa et al., 2019). The global trajectory of wind energy integration into mainstream energy systems reflects a paradigm shift in energy production. Ueckerdt et al. (2015) emphasise that wind energy is no longer confined to a supplementary or niche energy source; it has become a substantial contributor to overall electricity generation. The proliferation of wind farms across diverse geographic regions signifies global recognition of wind energy's potential to meet a significant portion of global energy demand (Ueckerdt et al., 2015; Bessa et al., 2019). Figure 2.7 presents the wind energy applications.

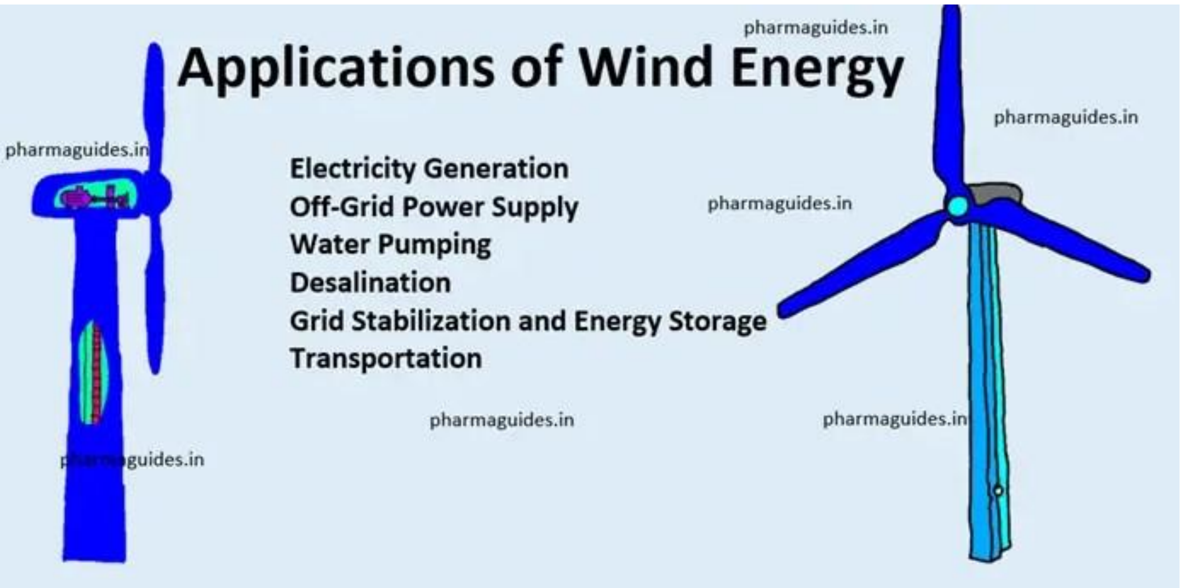


Figure 2.7: **Application of wind energy (El Zein, 2019)**

However, the journey towards realising the full potential of wind energy is not without challenges. Variability in wind power generation stands out as a key obstacle that necessitates a comprehensive understanding and strategic solutions to ensure the reliability and stability of the power grids (Ueckerdt et al., 2015; Valentine, 2011). This challenge is explored further in the subsequent sections, emphasising the critical need for innovative approaches to address variability while harnessing wind energy's environmental and economic benefits.

This technology has been seen making remarkable growth globally over the years and it has resolved a big energy crisis. While this technology is booming, it also has its challenges, which the researchers are aiming to resolve by introducing different means such as energy reserving/storage. Wind power is additionally utilised in off-grid or distant areas where connecting to the traditional power grid is not feasible or expensive. Autonomous wind turbines, often in conjunction with energy storage systems, provide a reliable means of generating electricity for remote communities, agricultural lands, and scientific facilities, thereby augmenting energy availability and resilience. Utilisations of wind power (López-Castrillón et al., 2021).

2.3.2. Wind Power Generation

As one of the most promising and competitive alternative energy sources in the midst of the present worldwide energy transition, wind power, in particular, is attracting significant attention from both the public and private sectors as a potential sustainable energy resource to be implemented. A major contributor to reducing greenhouse gas emissions and combating climate change, wind power generates clean electricity worldwide. In addition, nations that rely heavily on hydropower should diversify their energy portfolios, and wind power generation helps with that. Expanding the use of wind power necessitates a comprehensive understanding of its unpredictability and, consequently, reducing the uncertainties associated with wind power production.

When choosing the turbine platforms that best align with the data obtained and maximise output in the built wind farm, technical approaches such as forecasting and simulation provide better information. To support decisions on using BESS to reduce power production fluctuations that can lead to grid instability, this study provides a summary of the latest developments in wind speed and energy analysis. By addressing the critical demand for backup supply during uncertainties caused by wind variability, equipment failures, maintenance periods, and similar factors, BESS will optimise the efficacy of renewable energy sources and alleviate nearly all potential power generation fluctuations (Vargas et al., 2019).

Understanding how the wind changes over time and space is crucial across many branches of engineering and the physical sciences. Wind power is still a growing form of power generation; therefore, it's important to understand how it varies at different scales in the energy sector, even though the global economy isn't exactly clear. With the development of more powerful computers, it is now possible to predict future trends and wind speeds even in regions with sparse data (Watson, 2014). There is a lot of room for error when estimating the yield of a wind power plant, as the amount of energy produced varies greatly from year to year and season to season. Wind data collected on-site over one or more years is typically used for these evaluations. Records of wind speed and direction seldom go back more than three years. The long-term mean wind speed is presumed to be within ±10% of the average yearly wind speed fluctuations at the 90% confidence level. There has been no verification of this assumption for areas with high wind intensity; it is based on previous studies using long-term wind data from airports, solar parks, wind farm development sites, and similar locations. Plus, most energy-producing wind sites experience large seasonal variations in wind speed, which affect power output and introduce generation unpredictability.

A meteorological mast collects this data. Primarily, installations are set up to determine the amount of wind that can be harnessed in a given area, which then enables the construction of wind farms. This study examined the power performance of a large-scale wind turbine using a five-year field dataset from the meteorological tower at the planned building location. The wind veer characteristics were also considered. This data set included the turbine's operational parameters recorded in the SCADA system and the inflow conditions for wind veer characterisation retrieved from an advanced on-site met tower. At the Met Mast station, wind backing is more common than veering; however, there is a clear pattern suggesting a higher probability of veering winds of greater amplitude. This trend, which allows for the deduction of conclusions from acquired data, makes it easier to make educated judgments on the best platform for the chosen area (Gao et al., 2021).

The trend was determined by deriving a wind profile from the yearly wind data presented in Figure 2.8. Using this information, we can simply determine the wind speed at hub height and find the frequency of each possible outcome. A standard deviation of ±1 is shown by the error bars. With this information, we conducted a feasibility analysis to determine whether the selected location was a good fit for a wind farm. Properly sizing BESS to address the deficiency can be achieved by integrating data on seasonal wind limitations.

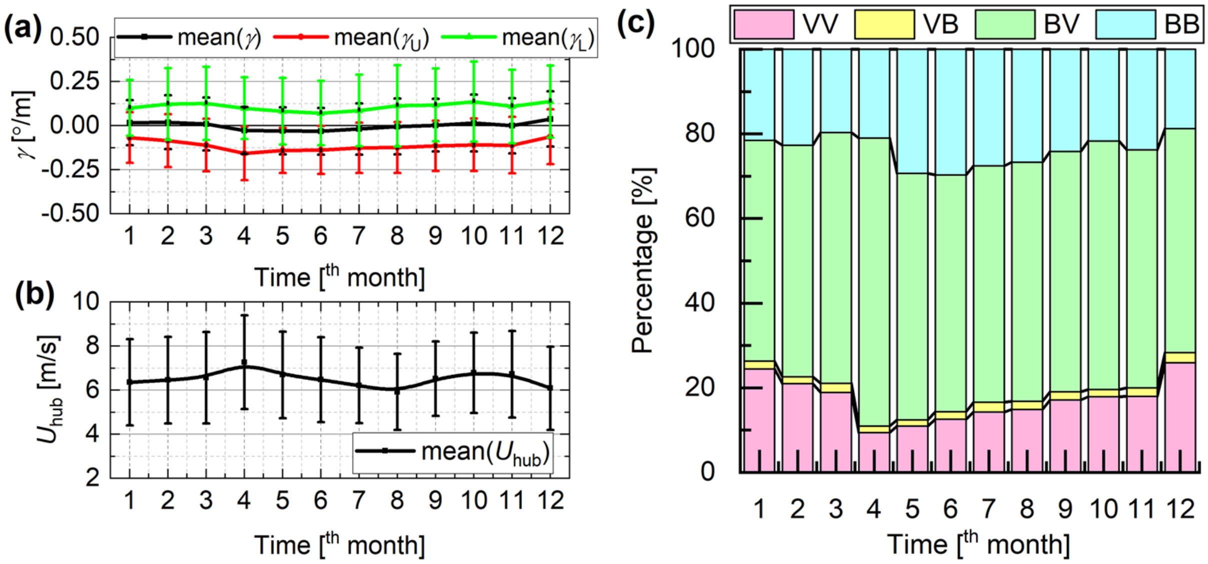


Figure 2.8: **The annual deviation of wind veer characteristics (Gao, Li & Hong, 2021)**

Together, the three frames provide a complete picture of annual wind characteristics:

1. Directional shear (a)
   – Mostly small, with mild upper- and lower-layer differences.
2. Wind resource strength (b)
   – Seasonal variation peaking in early year, lowest in late year.

3. Wind + stability regime frequencies (c)
   – Backing wind + stable atmosphere conditions dominate, with meaningful implications for turbine wake behaviour and fatigue loading.

While Figure 2.8 shows wind variations, the graph shows the power variations resulting from them, as the two are directly proportional. Figure 2.9 shows the power variation over a year, highlighting the effect of wind availability, which is influenced by factors such as sea breeze throughout the year, light, humidity, and other natural weather conditions.

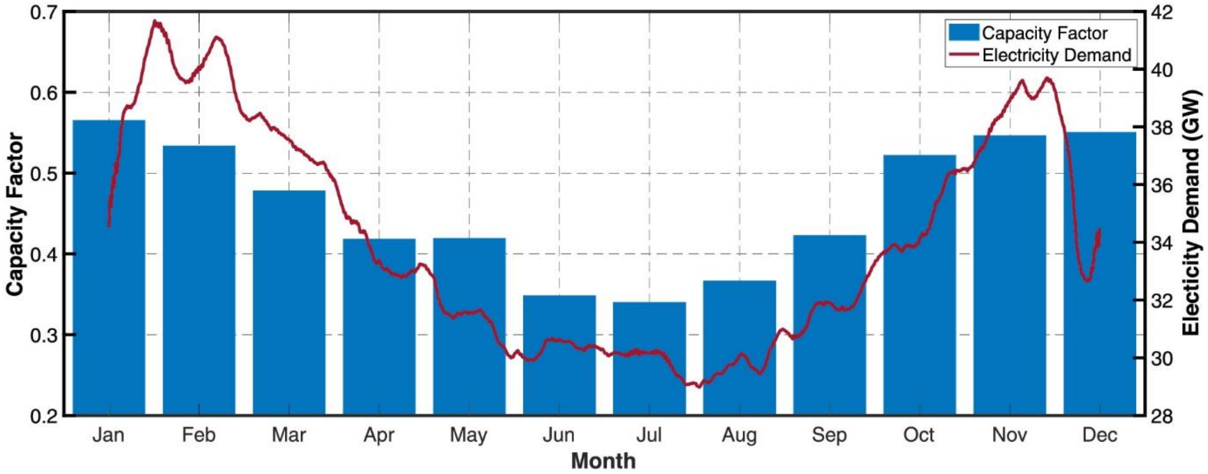


Figure 2.9: Annual variation of power output, presented in terms of monthly capacity factors (blue) (Potisomporn, 2021)

Intermittent nature: Wind energy is widely regarded as being highly intermittent and non-dispatchable due to its nature as a variable power source. This variability arises from a multitude of factors, including but not limited to wind speed, air density, and turbine attributes. Moreover, it is important to note that all these factors are further influenced by a site's geographical location. Therefore, this energy source is non-dispatchable without an energy storage system due to variations in wind generation and limitations during daytime and nighttime hours (Gao et al., 2021).

Variable energy output: Wind power fluctuates over time. To address the design heterogeneity of wind farms, the study proposed a new metric to quantify variations in power output across individual farms due to temporary changes in wind conditions. Most previous research on wind power variability has focused on wind power time series. While this approach makes sense when assessing actual wind power output, it poses challenges when planning and designing wind farms. There is currently limited knowledge of the expected time series of wind speed and direction the wind farm will encounter, and the wind farm's design has not been finalised. The researchers typically have wind measurement data from the last 2-3 years, allowing them to create historical time series for wind speed, wind direction, and local wind distribution. However, it's not reasonable to assume that these series will accurately represent the wind conditions that the wind farm will face in the future (Feng & Shen, 2017). These variabilities pose a threat to the power output fluctuations, which this study sought to mitigate through the implementation of BESS.

Need for backup: Since changes in wind power generation represent a continual threat to grid stability and safety, it is essential that wind farms have a backup power source. Incorporating dynamic control mechanisms is critical to ensuring the reliability and security of the power system that incorporates a renewable wind farm. Energy storage systems are becoming increasingly important in renewable energy due to recent advances in storage technology. More than a hundred years have passed since the invention of conventional energy storage technologies like lead-acid batteries and pumped or reservoir-based hydroelectric systems. Both conventional and cutting-edge methods of energy storage have seen a surge in popularity over the last decade (Gwabavu & Raji, 2021).

Storage solutions: Wind power is the primary energy source, requiring high-quality energy storage solutions, such as BESS. Among these options, the battery energy storage system shows significant potential, as evidenced by findings over the years (Gwabavu & Raji, 2021).

Forecasting and predictability: Wind forecasting occurs during the wind farm's developmental phases, predicting anticipated power output during operation and across various seasons. This is also simulated to corroborate the collected data. The results can ascertain the potential variations in power generation supplied to the grid.

2.3.3. Wind Power Variability

Wind power variability and net load variations across power systems are described in the literature. This presentation used real data collected over several years. The shown features encompassed the probability distribution for different ramp durations, variations over the day and season, and the occurrence of low-net-load events. Areas with low, medium, and high variability were discovered through the comparison. In areas with minimal variability, the maximum ramp observed within one hour was below 10% of the nominal capacity. Conversely, the maximum ramp may reach 30% in areas characterised by significant variability. The geographical scope primarily affects wind power variability, though an elevated capacity factor also contributes to increased variability. The analysis revealed autocorrelation and dependence of wind power ramps on operating output level. It has been noted that concentrated wind power in smaller areas results in outliers with substantial fluctuations in wind output, whereas well-dispersed wind power in larger areas does not (Kiviluoma et al., 2016).

The stochastic generation scheduling of short-term wind power scenarios significantly affects the reliability and operational costs of wind-integrated power systems. Figure 2.10 illustrates the power output fluctuations of wind farms across various regions throughout the year.

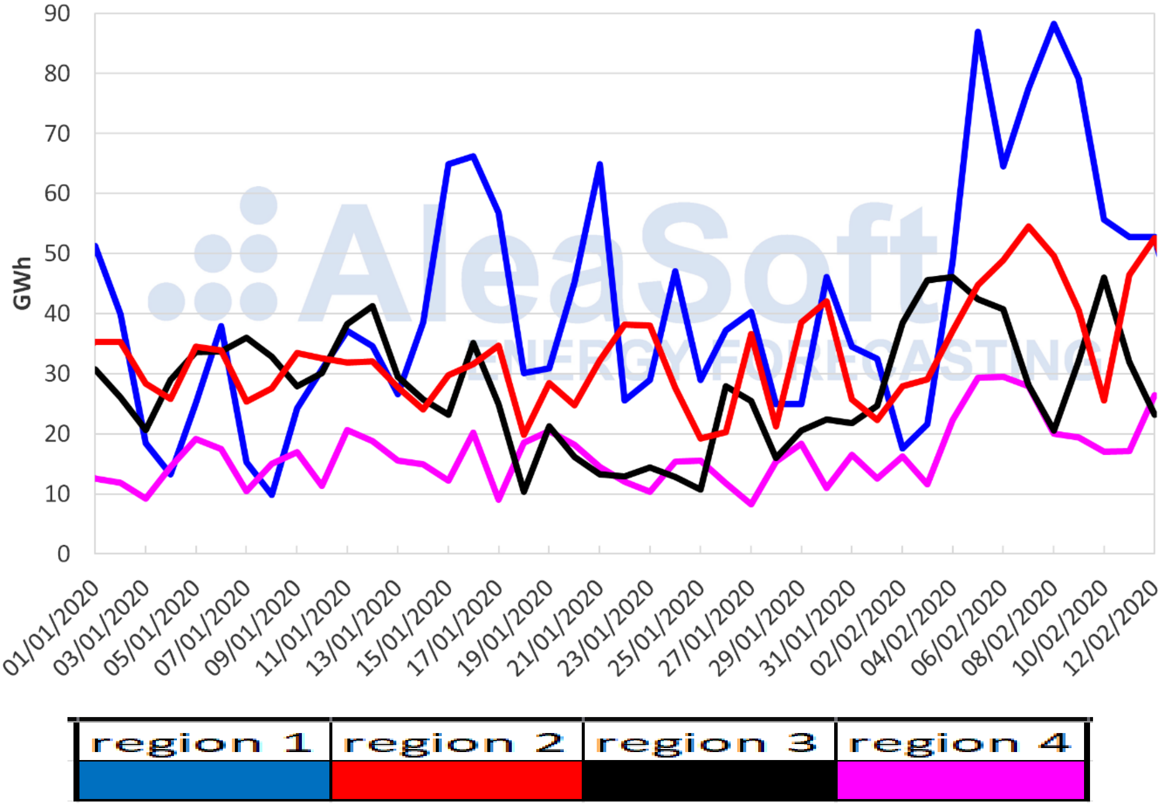


Figure2.10: **Wind energy variations in different wind farms (Wu et al., 2021)**

A scenario-generating approach was used to estimate expected variabilities and to gather the required data on forecast error and fluctuation distributions for short-term wind power. The paper characterised the forecast error as leading to power loss, which can be reduced with BESS. An inverse-transform sampling technique was used to draw from a multivariate normal distribution and produce many wind power scenarios. This distribution's covariance matrix was estimated to match the historical variations in wind power. After that, the suggested scenario-creation technique was applied to real-world total wind power data covering the entire power system in Ireland. The results show that estimating the critical range parameter within the multivariate normal distribution's exponential covariance structure can alter the variability of wind power conditions (Ma et al., 2013).

2.3.4. Challenges Associated with Wind Power Integration

As the world moves towards a low-carbon future, wind farms have proven to be a viable, long-term renewable energy option. The importance of integrating wind farms into the electrical grid has increased as the world strives to use cleaner energy sources, yet there are hurdles to overcome. The long-term sustainability of wind power depends on overcoming the obstacles currently hindering this process. One of the major problems with integrating wind farms into the power grid is the transient nature of wind energy. Wind farms generate electricity based on wind availability, which can be highly variable, whereas traditional power plants can be managed to maintain a stable output (Dent, 2012). The maintenance and reliability of this integration are crucial to achieving the stipulated operational duration, but technological advancement hinders this, as phasing out some components delays the repair of breakdowns and the smooth, on-time execution of maintenance.

Wind energy can be harvested to supply the whole of South Africa sufficiently. There are challenges to be resolved to fully pursue this integration, including, but not limited to, grid capacity availability and stability, utility infrastructure failures, and the grid expansion rate. Proper wind power integration will only be possible if the overall grid capacity and availability are there. South Africa has vast land and wind resources to support the introduction of wind power generation. Some parts of this available land have issues with evacuation routes for generated power, as there is no grid capacity to handle the generated power; hence, there are continuous breakdowns on the transmission lines. At times or in some seasons, the wind is not enough to fully supply the grid, which calls for the introduction and development of energy storage facilities (BESS, compressed air, superconducting magnets, underground pumped storage, and hydrogen storage). The choice is made based on the studies for each application or site and the efficiency of each application.

2.3.5. Energy Storage Efficiency

Concerns about the efficiency and resilience of global energy grids, the limitations on coal plant supply, the environmental impacts of fossil fuels, and the variability in renewable energy generation have led engineers and wind energy developers to prioritise energy storage. By storing energy, we can lessen the impact of wind power's unpredictable oscillations and, in certain cases, quickly adapt to large shifts in demand. This makes system response faster and reduces the need for backup power plants. Quick response time to demand changes, overall storage capacity, energy loss rate, and ease of charging are the four main factors that determine an energy storage facility's efficiency (Asri et al., 2021).

The spatial and temporal changes of the wind must be considered when wind power is integrated into energy networks. This will be more important in the future as wind power accounts for a larger share of the world's energy needs. This overview shows how well commonly used theoretical distributions fit observed data, and it emphasises the importance of understanding the site-specific distribution of wind speeds when calculating a wind turbine's capacity factor and energy yield. To study long-term geographical and temporal variability, we use model data analyses, proxy data (such as pressure fields), and surface observations. Climate change-related wind speed forecasts for several locations are summarised here (Watson, 2014). Inherent difficulties of wind power include, among other things, generating fluctuations in time that disrupt the grid, occurring on time scales ranging from minutes to seasons. As a result, maintaining a steady and reliable energy supply, along with the use of energy storage and alternative backup sources, becomes a new challenge when this ISRES is integrated into an electrical grid. For efficient management of energy production methods in such conditions, it is crucial to accurately forecast the output of these "unpredictable" energy sources. This comprehensive study clarifies the logic behind wind variation forecasting and highlights that renewable sources incur costs that can be substantial, due to their unpredictability and stochastic nature (Notton et al., 2018).

The volatility and unpredictability of wind resources pose challenges for grid operators. The deployment of BESS to combat the variations and intermittency of power generation is one of the complex procedures that must be implemented to sustain system equilibrium and decrease this variability. A more adaptable system is required to deal with the wide variety of supply-side variables, which in turn are correlated with generation levels and loads. In smaller or isolated electrical networks, the operator often struggles to balance demand and production using conventional, controllable energy sources. The capacity of the electrical system to adapt to disturbances, changes in production and consumption, and both anticipated and unanticipated changes is crucial to its reliability, as is the ability to keep customers' services uninterrupted and of high quality. Notton et al. (2015) found that deploying the BESS system during periods of reduced output will help this project.

Grid code compliance and standards for the country's grid compatibility provide a significant barrier to RES. Testing and compliance monitoring are carried out in areas where: Prior to being allowed to connect to the DS or the TS and begin commercial operations, all Renewable Power Producer (RPP) generators must show that they have followed all the rules and regulations stated in this grid connection code and any other applicable codes or standards approved by NERSA. Before generating an RPP, its creator must ensure it complies with all regulations laid out in this code by consulting with the System Operator (SO) and NERSA. To demonstrate that RPP meets all the specific criteria outlined in this code, the RPP generator must conduct experiments or studies. The RPP generator must ensure it follows all the rules for connections in this code in every important way. Before running any tests, each RPP generator must provide a thorough test method for each applicable section of this code, paying close attention to the effects on the system.

As soon as the RPP generator becomes aware that the RPP is not in compliance with any section of this code, whether through testing or another means, the RPP generator must notify the SO within one hour. Within that hour, the RPP generator must also provide the SO with a proposed plan to address the non-compliance and a proposed schedule for implementing it. In addition, as stated in Eskom Version 3.1 (2022), ensuring that the relevant RPP complies with this code requires diligently taking the necessary corrective action, regularly reporting to the SO in writing how the corrective measures are being implemented, and finally, providing satisfactory evidence to the SO that the relevant RPP is currently in compliance with this code.

South Africa is facing challenges in meeting the escalating energy demands driven by a burgeoning population and expanding industrialisation. An additional concern is the country's outdated energy infrastructure. These infrastructure components have become more unreliable due to inadequate maintenance and delayed updates, leading to breakdowns and power outages. Additionally, grid capacity constraints in other parts of the country and transmission and infrastructure failures have made it difficult to incorporate renewable energy sources into the energy mix. Inadequate investment in infrastructure has also played a role. Renewable energy sources, including wind power, have significant untapped potential in South Africa. But the country's capacity to put these renewable energy sources to good use has been limited by inadequate infrastructure. As a result, traditional coal-fired power plants continue to be the backbone of the nation's electricity generation, adding stress to the grid and making the energy situation worse (Setting up for the 2020s, 2019).

2.4. Integration of Battery Energy Storage System

To mitigate the inherent unpredictability of power output, battery energy storage solutions are essential, particularly for renewable energy sources such as wind. Using BESS provides a dynamic answer to the problem of renewable energy's intermittent nature by giving grid operators tools to control power supply and demand changes more efficiently. The crucial role of BESS in reducing power generation variability has been extensively documented in scholarly literature.

To reduce the unpredictability of renewable power sources, Bessa et al. (2019) emphasise the importance of energy storage systems, particularly battery storage. This study examined how BESS can be integrated into power networks, specifically how it can enhance grid stability by storing excess energy during peak generation and releasing it during low generation, thereby reducing swings.

Vargas et al. (2019) investigate how BESS mitigates the impact of variable renewable power generation on grid stability. The study examined how battery systems could be used to reduce the unpredictability of wind power, thereby making it more reliable and responsive to changes in demand. To maintain grid stability and provide a steady power supply, BESS acts as a stabilising agent by storing energy during periods of abundant wind and discharging it when production decreases. When it comes to wind power, particularly, Pryor et al. (2020) shed light on how to use batteries to reduce power generation variability. Findings showed that energy storage can improve variable wind generation by storing excess energy and releasing it strategically to match demand changes, according to the study's examination of the relationship between wind and BESS.

When it comes to making electricity systems more reliable, Ciupăgeanu et al. (2019) stress the need of battery storage. To keep the grid stable when renewable energy sources are unpredictable, BESS is crucial because it can respond quickly to changes in power generation. The technological considerations required in integrating battery energy storage into power systems are thoroughly examined in Gomez-Lazaro et al. (2013). By reducing the effects of intermittency, the study demonstrates how BESS may improve the reliability and quality of renewable energy integration.

2.4.1. Benefits of Integrating BESS with Wind Farms

Increased power grid stability and the financial viability of renewable energy programs are two major benefits of integrating BESS with wind farms. The potential benefits of this integration have been detailed in academic papers and studies, which show that it will improve grid stability and make wind energy more economically viable overall.

Improving grid stability is a key benefit of combining BESS with wind farms. According to Valentine (2011), energy storage plays a crucial role in providing grid stabilisation services through frequency management. The BESS stabilises the system by storing excess energy during periods of strong wind generation and releasing it during periods of low generation. This helps to match supply and demand and keeps the grid frequency within reasonable limits.

Adding BESS improves the economic feasibility of wind farms. Miettinen et al. (2013) examined the financial benefits of integrating wind power with energy storage devices. The research emphasises that BESS can increase the value of wind power by better utilising the generated power. A more stable, financially viable energy supply can be achieved through energy storage, which can reduce fluctuations in wind power output. This increases the reliability and predictability of energy generation.

The financial effects of BESS integration with wind farms were also considered in the study by Souza et al. (2019). Reducing the need for additional grid infrastructure and enhancing the overall economic sustainability of wind energy initiatives, the study emphasises the cost-efficiency of using energy storage to control the variations of wind output.

To make wind energy more economically viable, Lovholm et al. (2013) explain the benefits of combining wind farms with BESS. Energy storage has the potential to increase the monetary worth of wind power by reducing its intermittency and variability, according to the study. This would make wind farms a more attractive investment option. Berge et al. (2013) contributed to the existing body of knowledge by investigating the monetary and technological implications of integrating wind farms with battery energy storage systems. By providing grid support services and facilitating the integration of variable renewable power sources into the grid, energy storage can increase the economic feasibility of wind power projects, according to the research.

The key roles and causes that stoke interest in renewable energy integrated into BESS are that the resources are found worldwide and emit very little to no Greenhouse Gases (GHGs), which is referred to as "green energy" production. Renewable energy systems are being promoted based on several pieces of evidence that have been collected and presented. Secondly, the increasing price of gasoline and the unpredictability of its supply in certain regions of Africa are due to either inadequate infrastructure or the deterioration of older systems. When BESS was implemented, wind power operations and availability improved, and power generation variability decreased. This system ensures that the grid receives consistent power regardless of plant breakdowns or wind conditions (Karekezi & Kithyoma, 2002:1; Abanda, 2012:2148).

With the complex process of predicting electricity demand and organising and operating many power plants to meet those unpredictable demands, BESS plays a crucial role in reducing power generation variability by mitigating issues with electrical power systems. The instantaneous provision of electricity must always align with the steadily shifting demand, and the patterns of electricity demand during designated time intervals for electricity reliability within a selected geographical area. Some factors that impact seasonal and daily rhythms include the need for heating, cooling, and lighting. Although influenced by regional demand patterns, many general tendencies in demand patterns are widespread across the nation (Denholm et al., 2010). This integration is most suitable for eliminating the maximum power supply variations fed to the grid.

The output of wind power generation varies sporadically with wind speed. Uncertain variations in wind energy production could cause voltage and frequency disturbances in connected power systems. This research examined the use of BESS to mitigate the intermittency of wind power generation. There are two different frequency variations in the power output from renewable sources. A large-rated battery power (kW) but smaller-rated energy (kWh) is needed to reduce the rapid power perturbation. A large-rated energy (kWh) but smaller rated power (kW) battery is necessary for longer duration usage, such as time-shift and load levelling. (Godina, et al, 2016). Figure 2.11 illustrates the energy-saving solutions of BESS for efficient energy management.

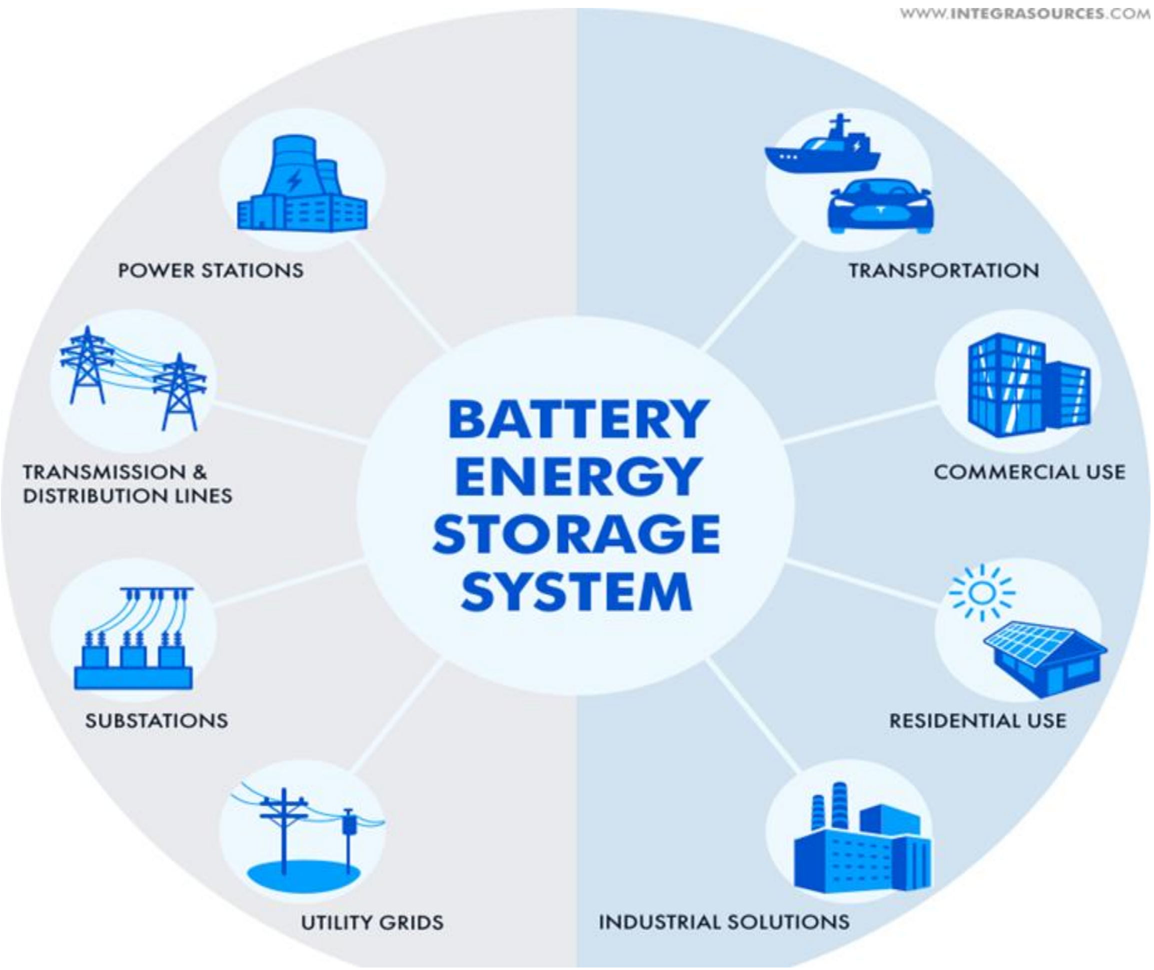


Figure2.11: **BESS energy saving solutions for efficient energy management (Konash & Narsr, 2022)**

Determining the most effective operation of BESS is the objective function of the microgrid. By bringing the present voltage closer to the prior period's average, it hopes to lessen voltage fluctuations (Tantrapon et al., 2020). By drawing on stored energy at times of peak demand, BESS can help lower the overall amount of electricity consumed at once. This can help reduce power bills by avoiding the more expensive need to buy power during peak hours (Lamy et al., 2016).

In the event of a grid outage or other emergency, BESS can dependable operate as a strong backup power supply. Healthcare facilities, data centres, and communication infrastructure are among the critical facilities that can receive continuous power from this source, ensuring their operations will not be disrupted (Hervas-Zaragoza et al., 2022). According to Jafari et al. (2022), BESS helps create a more sustainable energy system by reducing reliance on fossil-fuel power plants and increasing the use of renewable energy sources. This, in turn, reduces greenhouse gas emissions.

Optimal grid operation: By lowering transmission and distribution losses, BESS can be strategically used to improve the power grid through efficient power storage and discharge. The electrical system might become more efficient and save money as a consequence of this optimisation (Gwabavu et al., 2024). There are several environmental and financial benefits to using BESS, as it enhances the power grid's reliability, flexibility, and sustainability (Datta et al., 2021).

2.4.2. Technological Advances in BESS

Technological advancements in BESS have focused on charging rate, discharging rate, physical size, maintenance costs, and the lifespan of the system/technology. In this part, the transition and advancement of these are discussed as well as the improvements observed to assist in making good choices when these are to be integrated into the utility systems. Energy storage is widely recognised as a fundamental technology that enables the utilisation of renewable energy, particularly wind power. Additionally, distributed generation has the potential to contribute; however, it is important to note that the geographical positioning of wind resources and energy consumption are largely incompatible (Grosspietsch et al., 2019).

With the advancement of intelligent grids and microgrids, an increasingly evident need to preserve energy within power systems is evident. Many different methods for storing electrical energy have been developed throughout history. Different ways of storing electrical energy are fundamentally different from one another. Mechanical, electrical, thermochemical, chemical, electrochemical, and magnetic storage are all part of this category. Some well-known mechanical storage systems are compressed air, flywheels, and pumped hydro. Notable electrical storage technologies include capacitors and supercapacitors. Finally, Zvonimir et al. (2021) cite hydrogen fuel cells as an example of a chemical storage method.

Type LIB: Rechargeable batteries that use lithium ions move from the negative to the positive electrode when the battery is discharged and vice versa when the battery is charged (Qiao & Wei, 2012). The batteries have several advantages over lead-acid and other conventional secondary batteries. Long-life batteries (LIBs) have many desirable characteristics, including a high operating voltage, high energy and power densities, a low self-discharge rate, the absence of memory effect, and a wide operating temperature range (Vetter & Rohr, 2014). Despite the high production costs and the requirement for a specific charging circuit, these batteries are ideal for large-scale power storage due to their efficiency, safety, reliability, and lightweight design, as well as their extended lifespans (Huang & Jiang, 2011).

2.4.2.1. Lead-acid

Lead-acid batteries are regarded as one of the oldest and most cost-effective battery technologies currently available. They are extensively employed in automotive and industrial applications, as well as in power storage systems. It is noteworthy that these batteries exhibit high recyclability and operate with high efficiency at both high and low temperatures. A contemporary variant of these batteries, known as Valve-Regulated Lead-Acid (VRLA) batteries, surpasses its predecessors in lifespan, capacity, and maintenance. Nevertheless, this technology has some significant limitations, including slow charging, weight, and lower energy density (Lopes & Stamenkovic, 2020).

2.4.2.2. Nickel Cadmium (Ni-Cd)

Wearable electronics relied heavily on Ni-Cd batteries prior to the introduction of Li-ion batteries. These batteries offer a wide variety of layouts, prices, storage capacities, and resilience to low temperatures. In terms of energy density, self-discharge rates, and recyclability, however, the batteries lag their competitors. However, Ni-MH batteries, which are similar to Ni-Cd technology but use nickel oxide hydroxide instead, offer better features, such as higher capacity and energy density (Edström, 2020).

2.4.2.3. Flow batteries-vanadium redox

A new technical option for meeting the demand for massive energy storage, RFB, has recently surfaced. This is because its energy-to-power ratios are flexible and it can function in environments with ambient temperature. Unlike conventional batteries, the vanadium redox battery stores its electrolyte in tanks outside the battery, a feature first proposed in the late 80s. The battery can store energy through the concentration of ions because of this storage method. The active cell is charged and discharged by pushing the electrolyte through it. The anode and cathode blocks of the vanadium RFB use vanadium sulphate dissolved in sulphuric acid (H2SO4), which has different valence states (Venkatesan et al., 2022). Table 2.1 depicts the battery technologies used for energy storage.

Table 2.1: Battery technologies used for energy storage (Mexis, & Todeschini, 2020)

Battery technology	Types	Strengths	weaknesses
Lithium-ion	-Lithium cobalt oxide	-Light and compact	-High cost
	-Lithium manganese oxide	-High manganese oxide	-In flammability
	-Lithium iron phosphate	-High energy density	-Intolerance to extreme temperatures, overcharge and over discharge
	-Lithium nickel manganese cobalt oxide	-Low maintenance	
		-A long lifetime	
		-Easily and quickly charged	
		-A low self-discharge rate	
Lead-acid	-Flooded	-Very cheap	-Slowly charged
	-Sealed	-Highly recyclable	-Heavyweight
	-VRLA	-Operate effectively at both high and low temperatures	-Low energy density
	-GEL		
Nickel-cadmium	-Sealed	-Inexpensive	-Low energy density
	-Vented	-Easy to ship and store	-High self-discharge rate
		-Highly resistant to low temperatures	-Hard to recycle
Flow batteries	-Vanadium redox	-A very long lifespan	-Low energy capacity
	-Zinc-bromine	-High scalability	-Low charge/discharge rate
	-Zinc-iron	-Fast response time	
	-Iron-chromium	-Low risk of fires	

The unique benefits of flow batteries include a very long lifespan (up to 30 years), exceptional expandability, short reaction times, and little fire risk due to the non-combustible electrolytes they use. These attributes have firmly established flow batteries as a substantial portion of the market within on-grid and off-grid energy storage systems, particularly in sizable implementations (Vepa, 2020). It is essential to configure the BESS control system correctly to overcome the challenges that led to the integration of BESS with wind energy. The discharging and charging rates are controlled. When it comes to battery storage systems, the Energy Management System (EMS) oversees monitoring and controlling the energy flow. The EMS acts as the BESS's central coordinator, coordinating the functions of the BMS, PCS, and any other pertinent components. Through the compilation and examination of energy-related information, an EMS can effectively administer the power resources of the system (Wang et al., 2023) in this case energy management techniques are used.

2.4.3. Grid Services Provided by BESS

The potential for BESS to offer a range of grid services, increasing grid stability and reliability, has made its incorporation into the electrical grid a hot topic. Focussing on essential features including frequency regulation, voltage support, and ramp rate control, this critical literature study delves into the many facets of BESS's grid services.

2.4.3.1. Frequency Regulation

Maintaining a steady flow of power in response to user demand is the job of frequency regulation, an essential component of the grid. In the realm of frequency regulating services, BESS has become an invaluable tool. When it comes to dealing with the difficulties caused by the unpredictability of renewable power sources, particularly wind power, Ueckerdt et al. (2015) stress the significance of BESS. This study highlights the importance of BESS and how its fast response times can help with grid frequency regulation through power injection and absorption. In addition, the technical details of BESS in regulating frequency are investigated by Zhang et al. (2013). To optimise the reaction of BESS to frequency fluctuations, the research delves into the function of advanced control algorithms and energy management measures. Grid stability is enhanced by BESS, which helps to maintain optimal frequency levels by precisely controlling charge and discharge rates.

2.4.3.2. Voltage Support

To keep the electrical power quality within reasonable bounds, voltage support is essential. Voltage support services are provided by BESS through the regulation of voltage levels in response to grid variations. The capacity of BESS to improve grid resilience and its effect on voltage stability were examined in the study by Vargas et al. (2019). Findings highlight the potential of BESS to regulate voltage levels and enhance grid stability via controlled energy injection or absorption. Valentine (2011) explores the technical details of BESS's voltage support. The study highlights how BESS may actively contribute to voltage control through the use of advanced power electronics and grid-forming capabilities. When renewable energy sources are intermittent, BESS helps optimise grid performance by dynamically altering voltage levels.

Controlling the ramp rate is crucial for managing the rate of change in electricity generation or consumption. Ramp rate control services are a good fit for BESS because of how quickly it responds. To lessen the blow of sudden shifts in wind power and other renewable energy sources, Pryor et al. (2020) highlight the use of BESS. The study emphasises the capacity of BESS to stabilise the grid and alleviate strain on traditional power facilities by minimising power output fluctuations. Watson (2019) dug further into BESS's function in ramp rate regulation.

Finding out how BESS manages ramp rates depends on a number of technical elements and factors related to system design were the focus of the investigation. Even when renewable energy generation is quite unpredictable, BESS helps keep the grid stable and dependable by making rapid adjustments to power output.

The grid's stability and dependability are greatly enhanced by the combined contributions of BESS, which regulate frequencies, support voltages, and control ramp rates. The comprehensive effect of BESS on grid operation is highlighted by Wohland et al. (2019). To improve the electrical grid's overall resilience and dependability, the paper explains how BESS mitigates the problems caused by renewable energy sources' intermittency. Additionally, the financial considerations of deploying BESS for grid services are explored in Ciupăgeanu et al. (2019). Focussing on the long-term economic benefits linked to decreased system imbalances and improved reliability, the research assessed the cost-effectiveness of using BESS to increase grid stability.

2.5. Reliability of Grid Integration

To integrate renewable energy sources like wind into the current electrical grid architecture, grid integration is essential. Grid stability and reliability are impacted by this aspect's intrinsic fluctuation and intermittency, which presents simultaneous difficulties. To maximise the use of renewable energy and guarantee system balance, it is crucial to effectively manage this integration challenge (Jones, 2017). There is a threat to the reliability of the national grid because of this. Transmission systems link larger-scale power plants, whereas distribution systems link smaller-scale distributed power plants. Some challenges arise from attempting to directly integrate the two kinds of systems. Wind power has received a lot of funding as a result of the worldwide push to eliminate coal-fired power plants. On the other hand, obtaining high-quality power becomes challenging due to the unpredictable nature of wind speed. The reason behind this is that when the wind speed changes, it has a direct effect on the electric machine's voltage and active power output, which in turn causes grid instability. The use of BESS can reduce these differences. One way to deal with power outages is to use BESS as a source of compensation (Sandhu & Thakur, 2014).

Figure 2.4's wind power degeneration fluctuations further illustrate the grid's variability because of changes in wind speed; power inconsistencies lead to grid imbalances, which in turn cause grid collapse; and components experience strain as a result of having to adapt to the abrupt changes. The mentioned effect has an impact on consumers because there are times when they don't have access to a reliable energy source. When weather conditions are unfavourable, demand balance cannot be achieved. As a result, there has been an upsurge in research on

BESS, which was used to address these shortcomings. Transmission and distribution line upgrades are costly necessities for wind energy grid integration, and the often-remote sites of wind farms add to the maintenance burden. To support these integrations and withstand the continuous swings, the grid capacity needs to be appropriately expanded (Lamy et al., 2016).

Wind power's intermittent character, caused by variations in wind speeds, can have a major impact on the reliability of the power grid. Grid operators are compelled to employ modern technologies like energy storage and demand response to guarantee a steady and dependable supply of electricity due to this variability, which can cause frequency deviations and voltage changes. Smart grid management and control measures are crucial, says the South African Wind Energy Association (SAWEA), especially when wind power penetration is high. To efficiently react to the unexpected fluctuations in wind power production, spinning reserves must be readily available. The IEA suggests having enough reserve capacity to stabilise the grid, which means more investment and planning is needed to guarantee a steady supply of power (Mlilo et al., 2021).

Balancing the grid: Grid code compliance is a major challenge for integrating renewable energy into the national grid. Otherwise, there will be major issues, and maybe tripping, caused by PPC power quality not matching grid power quality. It is possible to further categorise the problems and issues surrounding the incorporation of wind energy conversion systems and other renewable power sources into the power grid into two separate groups: technical and non-technical. Following is a more detailed explanation of these groups.

a) Technical challenges: The technical challenges encompass a range of issues, including:

- Power quality, power fluctuation, storage challenges, protection issues, optimal placement of renewable energy sources, and islanding.
- Power quality refers to harmonics, frequency fluctuations, and voltage fluctuations.
- Power fluctuation involves short-term and long-term or seasonal power fluctuations.
- Storage challenges arise in the context of renewable energy sources.
- Protection issues pertain to safeguarding the system from potential hazards.
- Optimal placement of renewable energy sources involves determining the most advantageous locations for their integration.
- Lastly, islanding entails operating a portion of the power grid independently from the main grid.

b) Non-technical challenges

- In addition to technical challenges, non-technical challenges also play a significant role in the power grid. These challenges include:
- Limited availability of skilled technical workers.

- Insufficient transmission line capacity to accommodate renewable energy sources, and the exclusion of renewable energy source technologies from competitive markets.
- This exclusion discourages the installation of new power plants for reserve purposes.

2.5.1. Grid Integration Challenges

Frequency regulation, voltage support, and ramp rate control are some of the obstacles to grid integration of wind generation. The impact of electricity fluctuation on the stability and reliability of the grid is explained. Integrating renewable energy sources like solar and wind into the current electrical infrastructure is what's known as grid integration. Although renewable energy sources provide many benefits, there are still some challenges that need to be overcome before they can be integrated into the grid.

The fact that renewable energy sources are inherently unpredictable and only available at certain times is one obstacle. Renewable energy sources are intermittent and show more volatility than traditional power plants. This means that factors like the amount of sunshine or the speed of the wind determine their production. As a result, making sense of the grid's power consumption in relation to this unpredictability can be somewhat challenging (Impram et al., 2020). Adding to that, grid stability and reliability issues may emerge as a result of integrating large amounts of renewable energy. Voltage and frequency fluctuations caused by variations in renewable energy generation have the potential to affect the stability of the grid and cause power outages (Ourahou et al., 2020).

The constraints of the grid's architecture and system also give birth to a significant problem. Integrating renewable energy sources on a big scale may be beyond the capabilities of the existing grid infrastructure. Because of this, grid infrastructure upgrades are necessary to manage the additional capacity and solve technical issues including power quality, voltage management, and system protection (Datta et al., 2020). Integrating renewable energy sources successfully also requires efficient grid operation and planning. Renewable energy generation forecasting, demand-side generation scheduling, and grid management in real-time for efficient and dependable operation are all part of this (Wang et al., 2020).

Integrating renewable energy sources may also necessitate changes to the current market and regulatory structures. To achieve this goal, rules and regulations must be put in place to encourage the production of renewable energy and to equip grid operators with the tools they need to handle integration issues efficiently (Gjorgievski et al., 2022). Using storage and flexibility choices has become more important in order to reduce the difficulties caused by variations. One solution to the problems caused by renewable energy's unpredictability and intermittency is the installation of energy storage devices. One way to improve grid integration is to create more efficient and cheaper storage technologies. Another way is to look into flexibility options such integrated energy systems and demand response (Kohlhepp et al., 2019).

One of the many difficulties with wind power's grid integration is keeping the frequency constant through balancing power production and consumption. Because wind power is intermittent and subject to weather conditions, it is possible for grid frequency to deviate due to large generation fluctuations (Ahmed et al., 2020). Grid stability and the reduction of frequency deviations can be achieved by the use of frequency regulation methods, such as demand response programs or spinning reserves, which help to balance power supply and demand.

Keeping voltage levels within reasonable bounds is another obstacle to wind power integration. Voltage fluctuations and instability can occur as a result of the unpredictable nature of wind power, especially when wind power plants are located in remote places without sufficient transmission infrastructure. The ability of the grid to manage such oscillations can be compromised by the abrupt addition or removal of electricity (Han et al., 2014). Voltage control devices, reactive power compensation, and grid reinforcement are all necessary to handle this problem and make sure the grid is reliable.

The capacity of the grid to handle these variations can be compromised when wind power facilities undergo abrupt changes in production, a phenomenon called ramping, due to the unpredictability of wind conditions (Beaudin et al., 2014). To mitigate the effects of wind power output fluctuations, grid operators must adapt other generation sources, install energy storage systems, or employ sophisticated control procedures (Barra et al., 2021).

Because it throws a wrench into the power supply-and-demand balance, wind power's unpredictability has a major influence on grid reliability and stability. According to Shrestha and Gonzalez-Longatt (2021), voltage variations, frequency deviations, and grid instability can occur when wind power output suddenly changes. When the grid can't keep up with these unexpected changes in wind power generation, it can cause disruptions, voltage breakdown, or even power outages. Because wind power is unpredictable, extra steps like improved forecasting, grid infrastructure that can adapt to changing demands, advanced control systems, and energy storage technology are required to keep the grid stable and dependable (Jones, 2017). The difficulties and potential solutions to integrating wind power grids are shown in Figure 2.12.

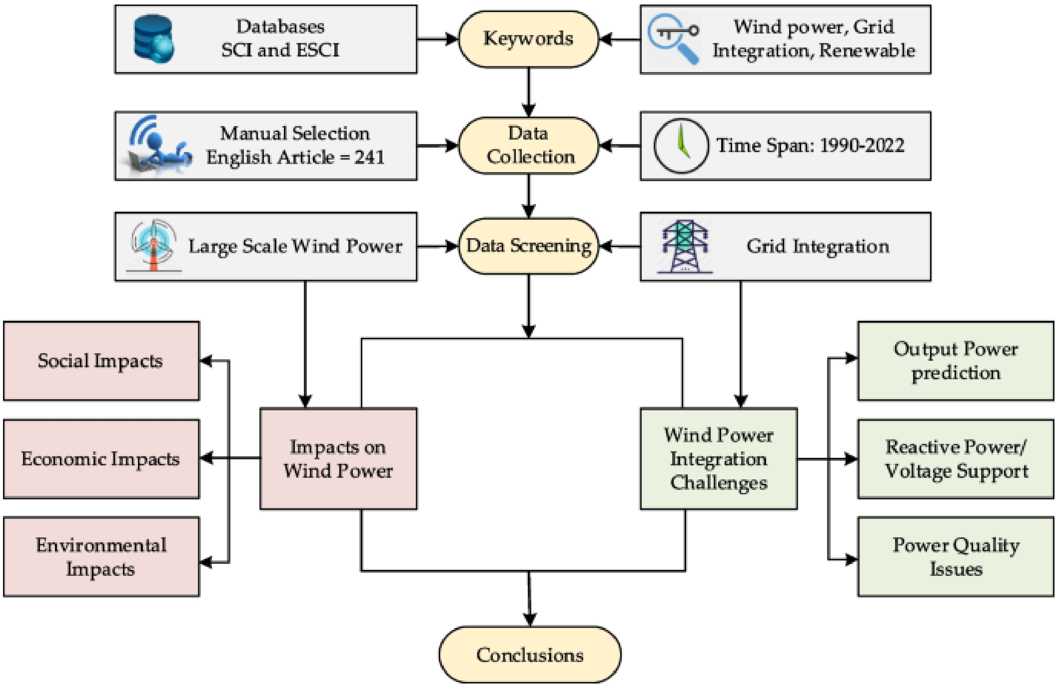


Figure 2.12: Wind power grid integration challenges and their solutions (Mastoi et al., 2023)

Addressing these challenges requires a comprehensive and interdisciplinary approach, collaborating with energy experts, policymakers, and industry stakeholders. By overcoming these challenges in grid integration, renewable energy can be effectively utilised to achieve a sustainable, reliable, and resilient energy system. Renewable energy has garnered substantial global attention because of its capacity to generate substantial amounts of energy while refraining from releasing greenhouse gases. The accessibility and cost-effectiveness of wind energy, along with its remarkable efficiency and technological advancements, have positioned it as one of the most auspicious renewable energy sources. Consequently, the capture of significant quantities of wind energy stands as an imperative in the present day. The comprehensive integration of wind power sources necessitates careful evaluation and mitigation to cultivate a sustainable future power system. The collaborative efforts of wind energy research and governmental entities are being deployed to surmount the potential obstacles associated with integrating wind energy into the power grid (Mastoi et al., 2023).

2.6. Optimal Sizing and Control Strategies

The determination of the dimensions of any technological platform necessitates a comprehensive examination that considers the technological requirements, objectives, and consumer demands. Similarly, in the case of integrating wind energy with BESS (Khalid et al., 2021), before project implementation, various aspects of the project are thoroughly studied. Evaluations are conducted to determine the appropriate dimensions of the wind farm along with its BESS integration. Strategies for managing the charging and discharging of the BESS system are established, ensuring that maintenance and spare part sources are synchronised with the operations to guarantee an efficient and stable power supply (Choudhury, 2022). The global interest in this integration has been substantial due to its capacity to deliver large-scale energy without the combustion of any fuels, thereby mitigating the greenhouse effect (Wang et al., 2022).

BESS serves as a dependable resource for fulfilling diverse power system applications. By incorporating BESS, the flexibility and reliability of renewable energy dispatch can be enhanced. Within the realm of power systems, wind energy holds the greatest significance among all renewable energy resources, making its control a focal point of research (Moghaddam et al., 2018).

2.6.1. Optimal Sizing of BESS for Wind Farm Integration

Determining the appropriate size of BESS is crucial for achieving optimal performance in wind farm integration. The work by Zhang et al. (2013) emphasizes the significance of sizing BESS based on the specific characteristics of wind farms, considering factors such as wind power variability and the intermittency of renewable energy sources. The study underscores the need for a comprehensive analysis of wind farm data to accurately size BESS and ensure effective energy storage and release.

Hodge et al. (2015) further contribute to the discourse on sizing BESS for wind farm integration by considering the temporal aspects of wind power generation. The research emphasises the importance of sizing BESS to align with the temporal patterns of wind power variability. By understanding the diurnal and seasonal variations in wind energy, optimal sizing can be achieved to capture excess energy during periods of high generation and release stored energy during periods of low generation.

Moreover, Litong-Palima et al. (2013) delve into the technical considerations for sizing BESS in wind farm applications. The study highlights the role of advanced modelling techniques in predicting wind power generation and determining the required storage capacity of BESS. By integrating meteorological data and wind turbine characteristics, optimal sizing strategies can be developed to enhance the overall reliability and efficiency of wind farm operations.

2.6.2. Control Strategies for BESS in Wind Farm Integration

Effective control strategies are pivotal for harnessing the full potential of BESS in wind farm integration. Pryor et al. (2020) emphasise the integration of wind forecasting techniques into

BESS control systems. The study explored how accurate wind forecasting enhances the ability of BESS to anticipate fluctuations in wind power generation. By adjusting the charging and discharging rates based on forecasted wind conditions, BESS can proactively respond to the changes in power output, thus optimising its contribution to grid stability.

The research by Sorensen and Cutululis (2015) delves into the role of energy market conditions in shaping control strategies for BESS. The study explored how market signals, such as electricity prices and demand-response mechanisms, can influence the operation of BESS in response to varying wind power scenarios. By aligning BESS operation with market dynamics, economic efficiency can be maximised, making wind farm integration more economically viable.

Furthermore, Dobschinski et al. (2013) contribute insights into the integration of wind turbine characteristics into BESS control strategies. The study explored how the dynamic behaviour of wind turbines, including the response times and power curves, can inform the optimal operation of BESS. By coordinating the actions of BESS with the inherent characteristics of wind turbines, synergies can be achieved to enhance grid stability and overall system performance.

2.6.3. Synergies in Control Strategies

Synergies in control strategies, where multiple factors are considered concurrently, offer promising avenues for maximising the benefits of BESS in wind farm integration. Lovholm et al. (2013) discuss the integration of wind forecasting, energy market conditions, and wind turbine characteristics in a holistic control approach. The study proposes an integrated control system that leverages real-time wind forecasts, market signals, and the dynamic response of wind turbines to optimise BESS operation. Such an approach aims to capture the inherent complexities of wind power generation, thereby leading to more effective grid services and enhanced reliability.

Additionally, Berge et al. (2013) investigated the potential of machine learning algorithms in optimising the control strategies for BESS in wind farm integration. The study explored how machine learning models can adapt and learn from real-time data, thereby improving the predictive capabilities of BESS control systems. By leveraging machine learning, BESS can dynamically adjust its operation based on evolving wind conditions, market dynamics, and turbine characteristics, thereby maximising its contribution to grid stability.

2.7. Environmental and Economic Aspects

The environmental implications of BESS integrated into wind farms can be thoroughly evaluated with the use of Life-Cycle Assessment (LCA) studies. The significance of life-cycle assessments (LCAs) in determining the total environmental impacts of energy storage systems has been highlighted by Bessa et al. (2019). Life cycle assessment (LCA) methods provide a comprehensive view of the environmental impact by taking into account the entire product life cycle, from extraction of raw materials through shipping, installation, operation, and final disposal. Ciupăgeanu et al. (2019) noted that BESS's environmental impacts can be more accurately assessed thanks to recent advances in life cycle assessments (LCAs). Embedded energy, emissions, and resource depletion are some of the life-cycle aspects considered in this study as they pertain to energy storage system design and operation. When it comes to the environmental sustainability of BESS integrated into wind farms, life-cycle assessments (LCAs) help make informed decisions by applying life-cycle thinking.

The environmental study is expanded upon by Valentine (2011), who investigates the possible advantages of combining wind power with energy storage. Results show that BESS can improve the integration of wind and other variable renewables by reducing spikes and maximising energy dispatch. Therefore, by guaranteeing a more consistent and effective use of renewable energy sources, this integration may reduce the total environmental effect. Considerations of cost-effectiveness and income generation potential are integral to any economic analysis of wind farm integrated BESS. The necessity for a thorough economic analysis is highlighted by Vargas et al. (2019), who investigate the financial viability of energy storage systems. Economic viability is crucial for general adoption, and the analysis takes that into account by considering things like capital costs, operations and maintenance expenses, and possible revenue streams.

The economic benefits of better grid stability through BESS are examined by Souza et al. (2019), who add to the economic conversation. Based on the study's findings, BESS can help improve grid reliability and economic efficiency by delivering grid services including frequency management and ramp rate control. The integration of BESS has the potential to optimise grid performance, which could lead to economic benefits that go beyond the immediate context of wind farm operation. In addition, Pryor et al. (2020) highlights the BESS economic consequences for wind forecasting. One way to improve the financial efficiency of energy storage is to incorporate accurate wind forecasts into BESS control algorithms. The study aimed to maximise the economic benefits of BESS integration in wind farms by minimising operational expenses and improving energy management through the use of advanced forecasting techniques..

2.8. Previous Studies for Wind Farm Integrated BESS

Real-world examples

Real-world applications of wind farm integrated BESS demonstrate the practicality and efficacy of this integration. Zhang et al. (2013) present a case study of a wind farm in which BESS was utilised to enhance grid stability and mitigate the variability of wind power. The study emphasises the successful integration of BESS, showcasing its ability to store excess energy during periods of high wind generation and discharging it during low wind conditions. Table 2.2 presents real-world examples of wind farm BESS studies, including the wind farm location, integration purpose, and the key findings.

Table 2.2: **Real-world examples of wind farm integrated BESS**

Study	Wind Farm Location	Integration Purpose	Key Findings
Zhang et al. (2013)	Coastal Region, USA	Grid stability, variability mitigation	Successful integration, improved grid stability
Ueckerdt et al. (2015)	Northern Europe	Load balancing, frequency regulation	Enhanced reliability, effective frequency control
Ciupăgeanu et al. (2019)	Onshore Wind Farm, Romania	Energy storage, grid support	Economic viability, reduced reliance on backup sources

Outcomes

The outcomes of integrating BESS with wind farms are multifaceted. Hodge et al. (2015) highlight the positive outcomes related to grid reliability. Their study demonstrates that BESS effectively contributes to frequency regulation, voltage support, and ramp rate control, thereby enhancing the overall stability of the power grid. The improved grid stability results in a more reliable energy supply. Table 2.3 presents the outcomes of the studies that focused on wind farm integrated BESS.

Table 2.3: **Outcomes of wind farm integrated BESS**

Study	Integration Outcomes
Hodge et al. (2015)	Enhanced grid stability, improved frequency response, reduced curtailment, and reliable energy supply
Valentine (2011)	Effective integration, reduced wind power variability impacts on the grid, increased reliability

Challenges

Despite the benefits, the challenges associated with wind farm integrated BESS are a subject of academic scrutiny. Vargas et al. (2019) identify the challenges related to the economic viability of BESS. The study underscores the importance of carefully assessing the economic aspects, including capital costs and potential revenue streams. Additionally, the challenges of efficient energy management and system optimisation are discussed, emphasising the need for advanced control strategies. Table 2.4 outlines the challenges encountered in real-world executed projects involving wind farm-integrated BESS.

Table 2.4: **Challenges on real-world executed projects**

Study	Challenges Identified
Vargas et al. (2019)	Economic viability, optimal energy management, technology optimization
Esteves et al. (2019)	Limited scalability, high initial costs, technology-specific challenges

Lessons learned

Several lessons have been learned from the implementation of wind farm integrated BESS. Sorensen et al. (2013) emphasise the significance of tailored control strategies. Their work suggests that adopting control strategies specifically designed for the variability of wind power enhances the overall performance of integrated BESS. This underscores the importance of customised approaches for different renewable energy contexts. Table 2.5 highlights the key lessons learned from the studies on wind farm integrated BESS.

Table 2.5: **Lessons learned from wind farm integrated BESS**

Study	Key Lessons
Sorensen et al. (2013)	Tailored control strategies enhance overall performance
Dobschinski et al. (2013)	Flexible energy storage configurations improve adaptability

Table 2.6 provides a comparative analysis of various BESS technologies, examining the characteristics, advantages, and limitations..

Table 2.6: **Comparative analysis of BESS technologies**

Study	BESS Technology	Key Characteristics	Advantages	Limitations
Løvholm et al. (2013); Linden & Reddy (2011)	Lithium-ion (Li-ion)	High energy density; high round-trip efficiency; fast response time; moderate-to-long cycle life	High power capability; compact size; suitable for grid services and renewable integration	High initial cost; thermal runaway risk; performance degradation over time
Weber et al. (2011); Soloveichik (2015)	Flow Batteries (e.g., Vanadium Redox Flow Battery)	Low–medium energy density; decoupled power and energy; very long cycle life	Highly scalable; deep depth of discharge; long operational life; enhanced safety	Low energy density; high capital cost; complex system design
Løvholm et al. (2013); Bhatia (2014)	Sodium–Sulphur (NaS)	High operating temperature (~300–350°C); high energy density; long discharge duration	Suitable for large-scale grid storage; long cycle life; high efficiency	Safety concerns; complex thermal management; high operating temperature
Rand & Moseley (1998); Bhatia (2014)	Lead-Acid	Low–medium energy density; mature technology; limited cycle life	Low cost; proven and widely available; recyclable	Heavy; short cycle life; limited depth of discharge; high maintenance
Linden & Reddy (2011); Kandasamy et al. (2016)	Nickel-Based (NiCd, NiMH)	Medium energy density; good tolerance to temperature extremes	Robust; reliable performance; suitable for harsh environments	Toxic materials (NiCd); moderate cost; memory effect

Table 2.7 summarises various studies on BESS, focusing on their aims, storage methods, used software or hardware, findings, and identified drawbacks. Each study highlights unique objectives, such as enhancing power system stability, integrating BESS with Photovoltaic (PV) systems, and mitigating renewable energy variability. Tools like DigSILENT, Matlab, and NREL's Measurement and Instrumentation Data Centre (MIDC) were used for simulations and analysis. The findings demonstrate the effectiveness of BESS in stabilising power output, ensuring profitability, and in maintaining system reliability. However, limitations such as unaddressed maintenance schedules, environmental concerns, and incomplete backup solutions were identified, indicating areas for further improvement in BESS applications.

Table 2.7: Summary of studies on BESS application

Papers	Aim	Method of storage	Used software/hardware	Findings	Drawbacks
Ujjwal Datta (2020)	Battery Energy Storage System for Renewable Energy Integrated Power System Stability Enhancement	BESS	DigSILENT	BESS consumption and utility availability are stabilised, no transformer overloading and the selling price ensures profit.	The research did not cover backup for breakdowns and maintenance schedules downtime.
Juha Majuri ('2017)'	Photovoltaic system with battery energy storage in Finnish residential use	BESS	DigSILENT	This thesis analysed the profitability of using a Battery Energy Storage (BES) system in parallel with a Photovoltaic (PV) system in Finnish residential applications.	In times of poor PV rays, no power is discharged to overcome the shortfall.
Hasnain ali (2022)'	Benefits of battery storage for wind power plant	BESS	DigSILENT	Delivering constant power to the grid for different periods is very visible and possible through the Bess.	BESS maintenance plan and schedule not tabulated/stated.
Daniela Andor (2015)	Energy storage systems for wind energy integration. Technology, applications, and benefit analysis	BESS	Matlab	All selected storage technologies were found to be best suitable for the service in terms of storage duration and self-discharge	As much as all storage platforms were found to be suitable for the problem at hand no specific storage platform was selected for the application.
Heath Alan Gurganus (2013)	Battery energy storage systems to mitigate the variability of photovoltaic power generation	BESS	NREL's Measurement and Instrumentation Data Centre (MIDC).	Based on the specifications included in the model for the different battery technologies, the sodium-sulfur, lead-acid, and vanadium flow battery types were consistent. seen to be the most feasible.	The material that provides a stabilizing effect in lithium-ion batteries and other types of batteries comes at a heavy environmental price and is not covered in this paper.
M. Zhang et al. (2021)	Optimizing Li-ion BESS for PV smoothing	Li-ion BESS	MATLAB/Simulink	BESS reduced PV ramp rate by 42%	Battery aging impact not studied

R. Singh & P. Kumar (2023)	Hybrid PV–BESS system for rural microgrids	BESS + PV	HOMER Pro	Hybrid system achieved 28% cost reduction	High initial capital requirement
T. Al-Sharif et al. (2022)	Grid-scale BESS for frequency regulation	Utility-scale BESS	PSCAD	Frequency deviation reduced by 60%	Limited evaluation of long-term reliability
A. Martinez (2024)	Evaluation of Na-ion batteries for grid storage	Na-ion BESS	Lab prototype testing	Na-ion proved cost-effective and safer than Li-ion	Lower energy density than Li-ion
K. Osei & Boateng (2023)	BESS for supporting weak African grids	BESS	DIgSILENT + ETAP	Voltage stability improved; outages reduced	Grid communication delays not modeled
F. Rahman et al. (2021)	EV-based distributed BESS for demand response	EV-BESS (V2G)	OpenDSS	Peak-load reduction of 19%	Dependent on EV charging behavior
L. Chen & Y. Hu (2020)	Artificial-intelligence-based control of BESS	BESS	Python + TensorFlow	AI controller improved SOC balancing and efficiency	Requires high-quality training datasets

2.9. The State of the Art and Gaps in Knowledge

2.9.1. State of the Art

The amalgamation of BESS with wind farms has become a fundamental technology to alleviate the intrinsic intermittency and variability of wind energy. The progress in BESS technologies, including lithium-ion, flow, and sodium-sulfur batteries, has yielded resilient and scalable energy storage solutions (Huang & Jiang, 2011; Vargas et al., 2019). The lithium-ion batteries continue to be the preeminent technology owing to their elevated energy density, extended longevity, and rapid charging capabilities (Gwabavu & Raji, 2021). Vanadium redox flow batteries are increasingly popular for large-scale energy storage because they allow for independent scaling of energy as well as power and possess extended operational lifespans (Venkatesan et al., 2022). This technological diversity allows the grid managers to choose storage solutions that correspond to certain applications, including frequency regulation, voltage stabilisation, and ramp rate control.

Recent advancements in EMS have markedly enhanced the operational efficiency of BESS. Modern energy management systems now include real-time wind forecasting, machine learning algorithms, and predictive maintenance to enhance the charging and discharging operations of battery energy storage systems (Pryor et al., 2020; Lovholm et al., 2013). This guarantees that the surplus energy produced during peak wind periods can be retained and judiciously released when wind generation diminishes, thereby offering a more consistent and dependable power supply. Gwabavu and Raji (2021) emphasise the significance of predictive control systems in improving the coordination between wind farms and BESS, thus facilitating smooth grid integration and minimising operational inefficiencies.

Grid integration analyses further illustrate the capacity of BESS to improve grid stability. Bessa et al. (2019) indicate that BESS facilitates grid functions such as frequency regulation and voltage support, hence efficiently alleviating power fluctuations resulting from wind speed variability. Successful case studies in Europe and in the United States have confirmed that BESS may stabilise electricity output, enhance grid stability, and prolong the economic feasibility of wind farms (Ciupăgeanu et al., 2019; Ueckerdt et al., 2015). Additionally, the research on the optimal size of BESS (Zhang et al., 2013) has proposed frameworks for aligning storage capacity with the temporal patterns of wind power, hence facilitating efficient energy storage and grid integration.

2.9.2. Gaps in Knowledge

Notwithstanding significant progress, substantial information deficiencies persist, especially about the ideal dimensions and economic viability of wind farm integrated BESS. Studies, such those by Zhang et al. (2013) as well as by Gwabavu and Raji (2021), emphasise the necessity of precise BESS sizing to align with the fluctuations of wind energy. The absence of standardised methodology and empirical validations of sizing models leads to an uncertainty about the scalability and performance of BESS in various wind farm settings. Economic obstacles, including substantial initial capital expenditures and overlooked maintenance costs, impede wider adoption. Vargas et al. (2019) emphasise that contemporary economic assessments frequently overlook end-of-life disposal expenses and resource availability, especially for lithium-ion technologies, thereby questioning the long-term viability of BESS integration.

The environmental sustainability of BESS technologies is a significant research gap. Although BESS markedly decreases greenhouse gas emissions by facilitating effective renewable energy usage, the ecological consequences of battery manufacturing, including the exploitation of limited materials such as lithium and cobalt, are insufficiently examined (Ciupăgeanu et al., 2019). Gwabavu et al. (2021) advocate for additional investigations into alternate energy storage chemistries, including sodium-ion and hydrogen-based systems, which may provide more sustainable options. Moreover, thorough life-cycle assessments of BESS technologies are essential to tackle issues with recycling, second-life applications, and the environmental repercussions of extensive battery deployment.

Incorporating BESS into antiquated grid infrastructures poses a considerable challenge, especially in emerging areas like South Africa. Gwabavu and Raji (2021) underscore the inadequacies of ageing transmission networks, which cannot support the fluctuation and magnitude of wind power integration. Confronting these difficulties necessitates substantial expenditures in grid modernisation, smart grid implementation, and regulatory frameworks to guarantee adherence to grid codes and standards. The absence of legislative incentives and institutional backing exacerbates these constraints, hindering the implementation of integrated renewable energy solutions.

Furthermore, although progress has been achieved in control techniques for BESS operation, their practical use is still constrained. Pryor et al. (2020) illustrate the efficacy of incorporating wind forecasting into BESS control systems; but still, additional research is required to create adaptable and intelligent algorithms that can dynamically react to unpredictable wind patterns and changing grid conditions. Promising, machine learning-based control techniques necessitate further validation to guarantee scalability and robustness across various geographical and operational contexts (Lovholm et al., 2013).

Despite considerable advancements in wind farm integrated BESS technology, deficiencies remain in appropriate sizing, cost efficiency, environmental sustainability, and control methodologies. Addressing these gaps through interdisciplinary research, policy advocacy, and practical case studies is crucial for optimising the potential of BESS in attaining a stable, resilient, and sustainable energy future.

2.10. Summary

This chapter offered a comprehensive examination of the literature regarding integrating BESS with wind farms, highlighting their function in alleviating wind power generation's intrinsic variability and intermittency. The chapter examined improvements in BESS technology, energy management systems, and control methodologies that improve grid stability and reliability. Practical applications and case studies emphasised the benefits and challenges of integrating BESS, including economic feasibility, proper sizing, and environmental sustainability. Notwithstanding considerable advancements, substantial deficiencies persist, especially in establishing standardised procedures for BESS size, tackling environmental issues associated with battery production and disposal, and upgrading antiquated grid infrastructure. These shortcomings highlight the necessity for additional interdisciplinary research and novel solutions to enhance the performance and sustainability of wind farm-integrated BESS. This literature review established the foundation for the following chapters, tackling these difficulties and enhancing the continuing conversation on renewable energy integration for a stable and sustainable future.

CHAPTER THREE

METHODOLOGY

3.1. Introduction

This research aim to highlight one the methods to resolve power outages, improving the stability of the national grid, and facilitating the integration of renewable energy sources like solar and wind all depend on energy storage systems (ESS). To lessen the impact of renewable energy sources' inherent unpredictability, this chapter centres on combining BESS with wind power. Improved energy utilisation, system efficiency, and power reliability are all possible outcomes of BESS's efforts to mitigate uncertainty and intermittency (Liu et al., 2020).

Integrating BESS with wind farms offers opportunities to optimise energy dispatch, minimise reliance on auxiliary grid power during faults, and stabilise output across varying wind speeds. For instance, wind turbine output fluctuates with wind speed, which ranges from minimum operational levels to cut-off thresholds. BESS integration smooths these fluctuations, providing consistent and dependable energy output (Amrr et al., 2018).

To achieve optimal integration, this research explored the sizing and configuration of BESS components to address challenges such as battery degradation, operating costs, and power flow dynamics. Advanced models for capacity allocation were employed, considering both active and reactive power optimisation, voltage deviation mitigation, and absorptive capacity for renewable energy. These models incorporate extreme scenarios and uncertainties in renewable energy data, using advanced optimisation techniques like mixed-integer linear programming to ensure robust system performance (Datta et al., 2021).

By combining theoretical insights, real-world data, and simulation-based validation, this research aimed to develop a comprehensive methodological framework. Key focus areas included wind resource assessment, BESS technology evaluation, and regulatory compliance. Ultimately, integrating wind energy with BESS enhances grid stability and aligns with sustainability goals, thereby ensuring reliable and efficient energy solutions.

3.2. Theoretical Framework

3.2.1. Wind Farm

A horizontal axis wind turbine onshore wind farm is the subject of this study investigation. As a result, the chapter highlights the building process, energy extraction, and grid integration.
Wind turbine power extraction

The aerodynamic power extractable by a wind turbine is determined by key factors such as air density ($\boldsymbol{\rho}_{\text{air}}$), rotor swept area ($\boldsymbol{A}_{\text{rotor}}$), the aerodynamic efficiency of the rotor ($\boldsymbol{C_p}$), and the cube of wind speed ($\boldsymbol{u}$). This relationship is expressed in equation 3-1:

$$\boldsymbol{P}_{\text{w}} = \frac{\mathbf{1}}{\mathbf{2}} \boldsymbol{\rho}_{\text{air}} \boldsymbol{A}_{\text{rotor}} \boldsymbol{C_p} \boldsymbol{u^3} \tag{3-1}$$

Where:

$\boldsymbol{P}_{\boldsymbol{w}}$: Aerodynamic power extracted by the turbine (W).

$\boldsymbol{\rho}_{\text{air}}$: Air density (kg/m^3).

$\boldsymbol{A}_{\text{rotor}}$: Rotor swept area (m^2).

$\boldsymbol{C_p}$: Aerodynamic efficiency of the rotor (power coefficient).

$\boldsymbol{u}$: Wind speed (m/s).

It is not possible to fully harness the wind's kinetic energy due to limitations in energy conversion. At 59% theoretical maximum efficiency, or the Betz Limit, 59% of the wind's kinetic energy may be transformed into usable electricity. The power coefficient (C_p) of the rotor is affected by the blade pitch angle (β) and the rotor tip-speed ratio (λ). A blade's tip-speed ratio, as defined in equation 3-2, is the ratio of that speed to the wind speed:

$$\boldsymbol{\lambda} = \frac{\boldsymbol{\omega r}}{\boldsymbol{u}} \tag{3-2}$$

Where:

$\boldsymbol{\lambda}$: Tip-speed ratio (dimensionless).

$\boldsymbol{\omega}$: Rotational speed of the rotor (rad/s).

$\boldsymbol{r}$: Rotor radius (m).

$\boldsymbol{u}$: Wind speed (m/s).

The angle between the blade's chord and the plane of rotation is called the blade pitch angle (β), which can be seen in Figure 3.1.

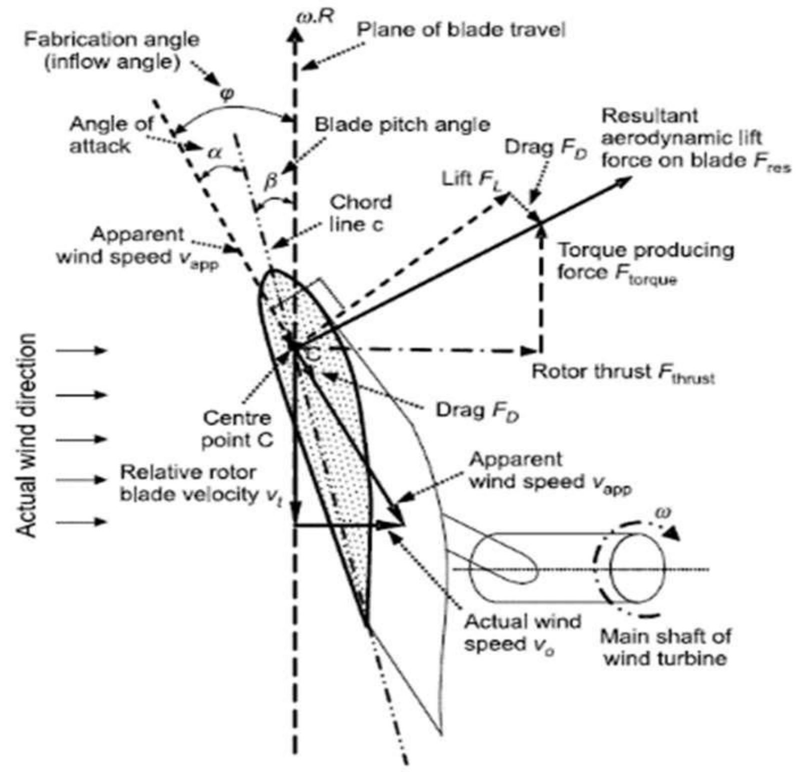


Figure 3.1: **Rotating wind turbine blade forces (Joshua & Sthuthi, 2019)**

Figure 3.2 shows the variation of the power coefficient. By optimising λ and β, the rotor can achieve maximum power extraction (C_p) under given wind conditions. These parameters are critical for designing and controlling wind turbines for efficient energy extraction.

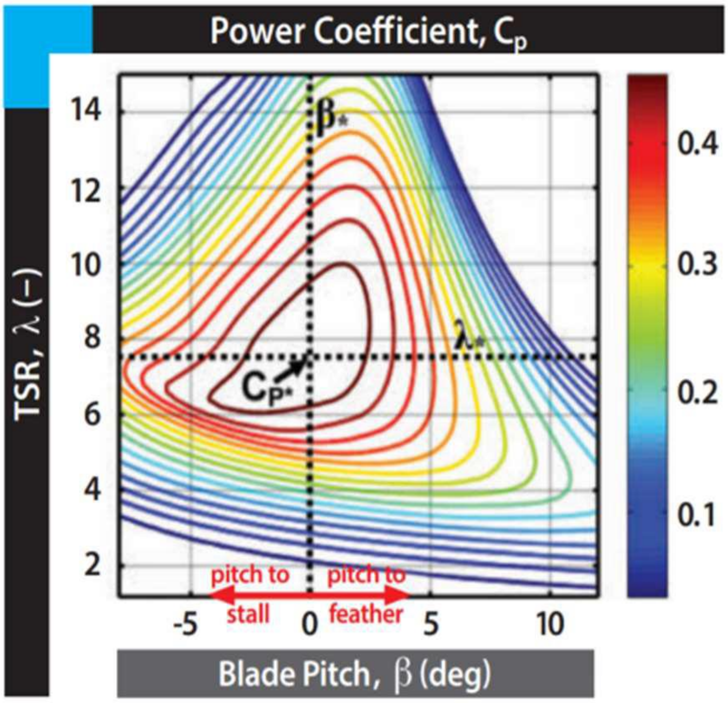


Figure 3.2: **Power coefficient characteristics of a turbine** (Aho et al., 2013)

A wind turbine's power curve illustrates how much energy it can produce using the wind resource. It shows the correlation between the wind speed at hub height and the turbine's electrical power output (Burton et al., 2011). The power curves for pitch-controlled wind turbines are typically displayed as in Figure 3.3.

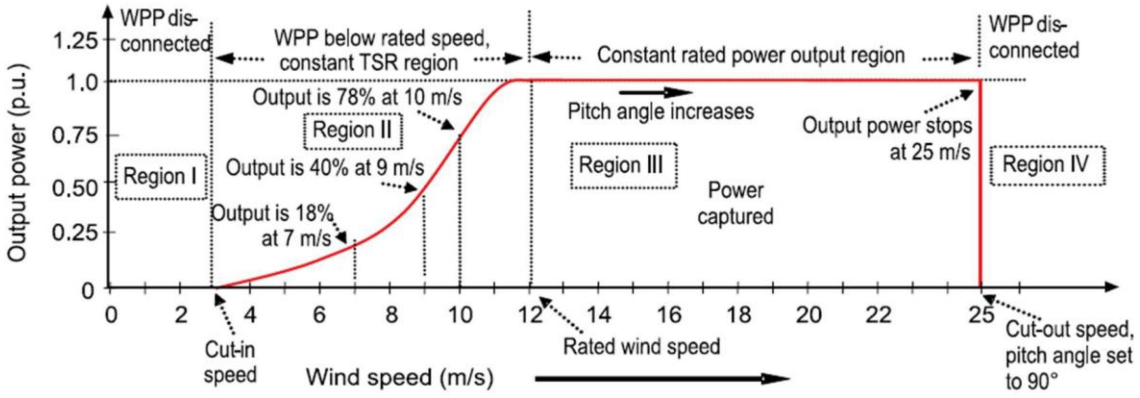


Figure 3.3: **Wind turbine power curve (Joshua & Sthuthi, 2019)**

The power curve is divided into four distinct operational regions, each defined by the primary objectives of the turbine's control system (Hau, 2013; Joshua & Sthuthi, 2019). The operational regions of the wind turbine power curve;

Region 1: The wind turbine in this area is waiting to provide electricity. However, internal losses cannot be overcome by the available wind speed. Power generation begins when the wind speed reaches the turbine's cut-in speed, which is continuously monitored by the turbine.

Region 2: This operating phase takes place when the wind speed falls between the cut-in and rated wind speeds. The turbine runs at its highest aerodynamic efficiency in this area. The turbine's rotational speed is controlled to smoothly go into the next area when the wind speed gets closer to the rated value.

Region 3: The turbine runs in Region 3 when the wind speed falls between the cut-out and rated wind speeds. Maintaining functioning within the structural and electrical load limits is the main goal of the control system in this area. The turbine accomplishes this by pitching the blades to maintain a steady rotational speed.

Region 4: The wind turbine in this area is turned off to protect it from high structural and electrical loads brought on by wind speeds beyond the cut-out threshold. This guarantees the turbine's lifetime and safety.

3.2.1.1. Weibull Distribution for Wind Resource Representation

A Weibull distribution, which simulates the frequency of varying wind speeds, is commonly used to depict the wind resource at a site. The Weibull distribution is expressed mathematically as:

$$f(u) = \frac{k}{A}\left(\frac{u}{A}\right)^{k-1} \exp\left(-\left(\frac{u}{A}\right)^{k}\right) \tag{3-3}$$

The frequency distribution of wind speed u the function represents u $f(u)$. The scale and shape parameters are denoted by the variables A and k, respectively. These parameters are estimated from measured data and are site-specific. The total wind speed distribution is described by the scale parameter A , which has the same unit as wind speed and is proportional to the location's mean wind speed. Conversely, the distribution's form is defined by the unitless shape parameter k.

Typically, the value of k ranges from one to three, where k =1 indicates high wind fluctuations and k =3 suggests more stable winds (METEOTEST, no date). The Weibull distribution graphs for various k values are shown in Figure 3.4, emphasising how k affects the distribution's form. The scale parameter A has been maintained at 10 in this case.

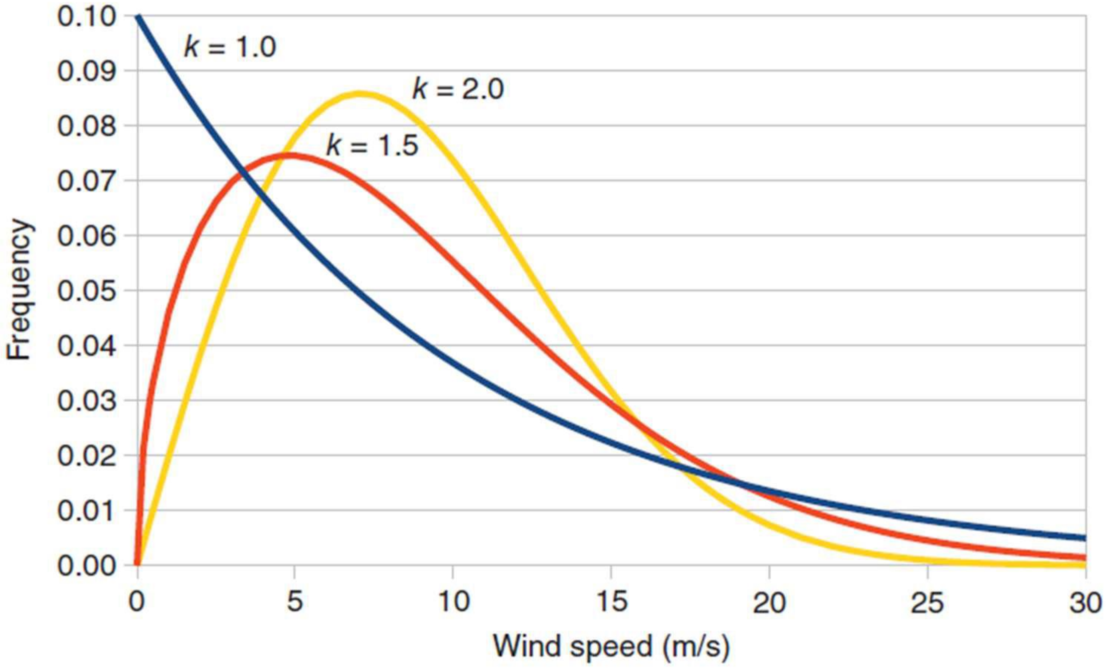


Figure 3.4: **Distribution of Weibull (Landberg, 2015)**

Equation 4 represents the power curve and the available wind resource's Weibull distribution, which can be used to compute the overall energy production of a wind farm (Landberg, 2015):

$$AEP = \sum_{u_{\text{min}}}^{u_{\text{max}}} \sigma_u [P_{\text{WT}}(u)] \times n_{\text{WT}} \times T \tag{3-4}$$

The AEP is the sum of all the energy that a Wind Turbine Generator (WTG) produces during a certain time frame, usually a year. The cut-in wind speed (u_{cut-in}) is the lowest wind speed at which the turbine begins to generate electricity, and the cut-out wind speed ($u_{cut-out}$) is the highest wind speed at which the turbine stops to avoid damage, so incorporating both of these components is crucial. With the help of the Weibull distribution, we can determine the likelihood of a particular wind speed (σ_u) and then compute the power output of the turbine ($P_{\text{WT}}(u)$) under those conditions. Additionally, the method takes into consideration the total number of wind turbines (n_{WT}) and the total amount of time (T), which is around 8,760 hours for an annual calculation. When all these variables are included, AEP provides a complete picture of the turbine system's annual energy production.

3.2.1.2. Topologies of Wind Turbine

Wind energy conversion systems utilise various electrical generators, each tailored to specific applications and requirements. This section provides an overview of the major types of generators employed in WECSs, emphasising that the Chaba Wind Farm relies on Doubly Fed Induction Generators (DFIGs), which form the primary focus of this study. Figure 3.5 depicts an overview of electrical generators for wind energy conversion systems.

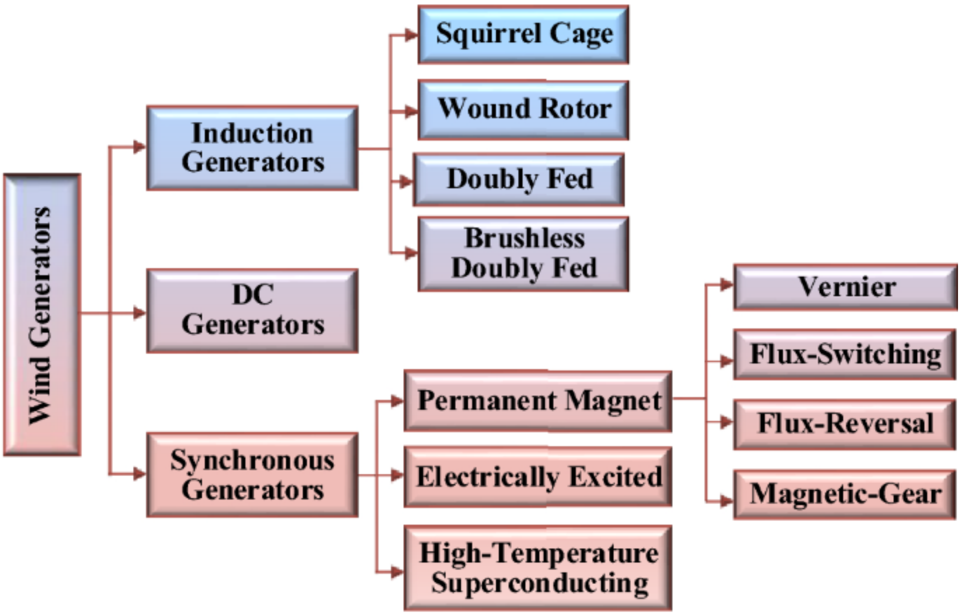


Figure 3.5: Wind generators (Mostafa et al., 2022)

Historically, DC generators have been used in low-power standalone wind systems due to their simplicity and suitability for low-voltage applications. However, their usage is limited to very small wind turbines, and they are not practical for large-scale systems. Modern wind energy systems predominantly employ AC generators, which are better suited for high-power applications. Among these, induction and synchronous generators are the most used, each offering distinct advantages and challenges. Induction generators include Squirrel Cage Induction Generators (SCIGs) and Wound Rotor Induction Generators (WRIGs). SCIGs are known for their reliability, low cost, and maintenance-free operation, thus making them a widely accepted choice for fixed or semi-variable speed systems. However, their significant drawbacks include the need for a gear system and large starting currents. WRIGs address some of these issues by introducing external resistances connected to the rotor via slip rings, enabling improved starting torque and lower inrush currents. Despite these advantages, WRIGs require periodic maintenance due to the use of slip rings and brushes (Mostafa et al., 2022).

Doubly Fed Induction Generators (DFIGs) are an advanced form of WRIGs and are the most widely used generators in modern wind farms. Figure 3.6 illustrates the DFIG structure, where control is achieved via the Machine-Side Converter (MSC) and the Line-Side Converter (LSC) using decoupled current control.

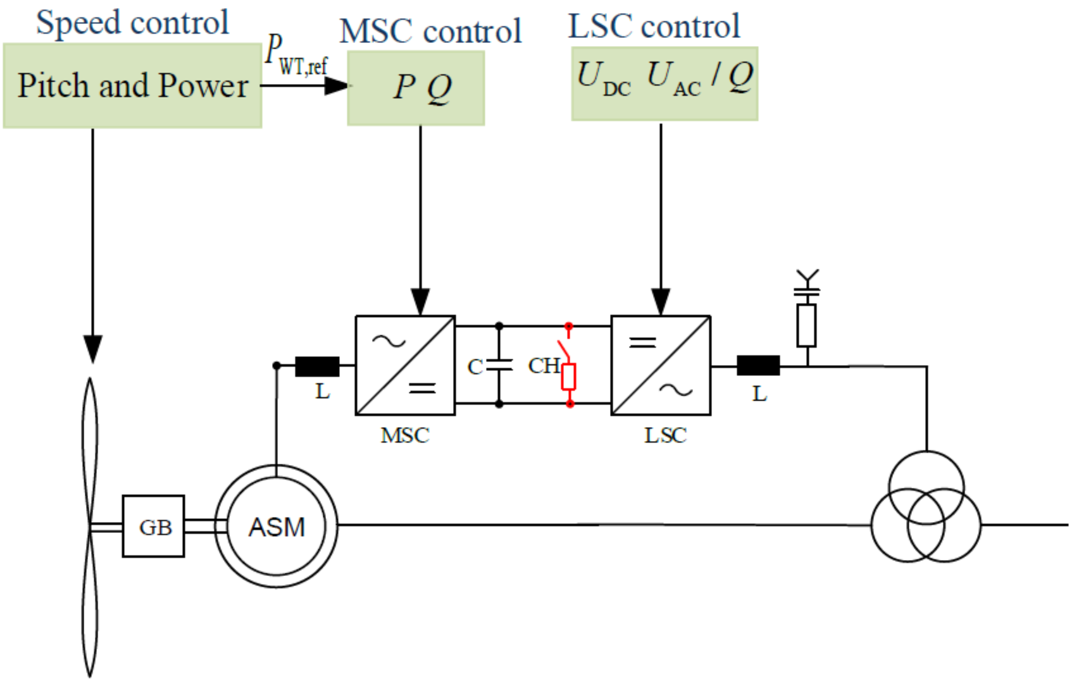


Figure 3.6: Doubly fed induction generators structure (Boroujeni, 2020)

DFIGs incorporate a wound rotor connected to a controller, enabling precise control of active and reactive power, as well as compensation for turbine speed fluctuations. MSC regulates active and reactive power, while LSC maintains DC link voltage and manages the grid power exchange. A DC link chopper protects converters from high DC voltages by switching based on pre-set thresholds. Their ability to operate efficiently across a broad range of wind speeds makes them ideal for variable-speed wind systems. Although DFIGs still require slip rings and brushes, their operational flexibility and widespread adoption have solidified their dominance in the wind energy market (Boroujeni, 2020).

Synchronous generators are another prominent category used in WECSs. Electrically Excited Synchronous Generators (EESGs) use DC excitation via slip rings or brushless exciters. While efficient, EESGs require a large number of rotor poles to achieve the necessary turbine speeds, thereby increasing complexity. Permanent Magnet Synchronous Generators (PMSGs), on the other hand, have gained popularity due to their high efficiency and reliability. By eliminating the need for external excitation, PMSGs reduce maintenance requirements. However, the high cost of permanent magnets has been a limitation, although recent price reductions are making PMSGs increasingly attractive (Zhong & Weiss, 2011; Conroy & Watson, 2009).

Brushless Doubly Fed Induction Generators (BDFIGs) have emerged as a promising technology by eliminating slip rings and brushes, thereby reducing maintenance and increasing reliability. Despite these advantages, BDFIGs are still in the research phase due to the challenges associated with their practical implementation. Innovative technologies such as High-Temperature Superconducting Generators (HTS-SGs) and modified PMSGs, including vernier, flux-switching, and flux-reversal designs, are also being explored to enhance efficiency and torque density. These advanced designs aim to address specific challenges in wind energy applications, such as reducing reliance on gear systems and improving energy capture at varying wind speeds (Mostafa et al., 2022).

At the Chaba Wind Farm, DFIGs are utilised for wind energy generation. This choice aligns with industry trends, as DFIGs account for approximately 48.6% of global wind turbine applications. Their adaptability to variable wind conditions and efficiency in power control make them a preferred option for large-scale wind farms. Consequently, this study focused on DFIGs to evaluate their performance and contribution to wind energy systems.

3.2.1.3. Internal Collector Network for Wind Farm

The power from wind turbines is sent to the grid using the wind farm's internal collector network, which can do it directly or through a transformer system called the Grid Substation (GSS). The GSS wind turbine transformers, and cables (both underground and above ground) are essential parts of this network (Smail et al., 2018). As illustrated in Figures 3.7 and 387, common topologies encompass radial (thread), star, tree, and loop layouts.

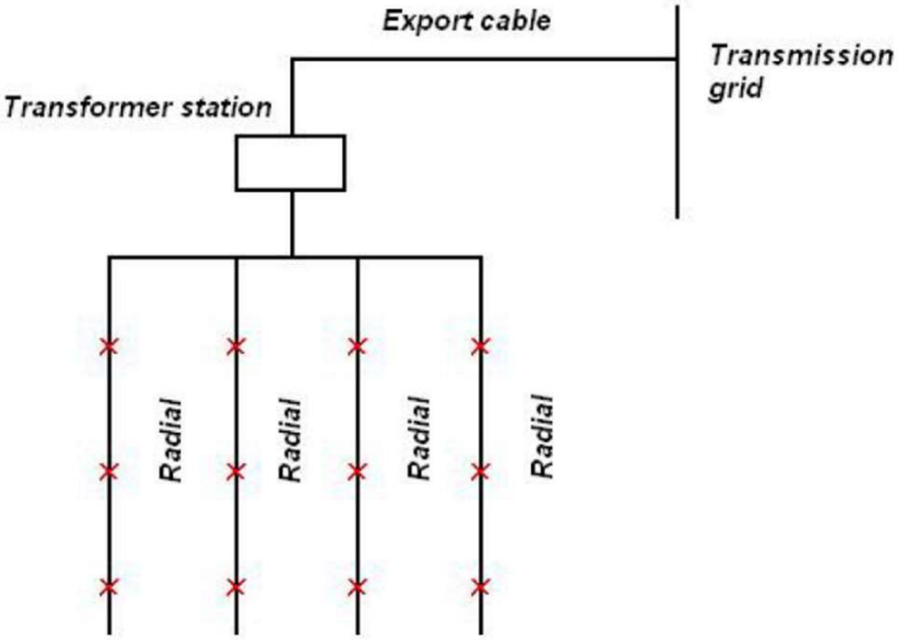


Figure 3.7: Wind farm's internal grid structure

Radial topology, though cost-effective, suffers from lower reliability due to single points of failure, while star and tree topologies improve reliability at higher costs. The loop topology offers the highest reliability with redundant paths but incurs the highest cost. This study examined a hybrid network with both tree and radial topologies.

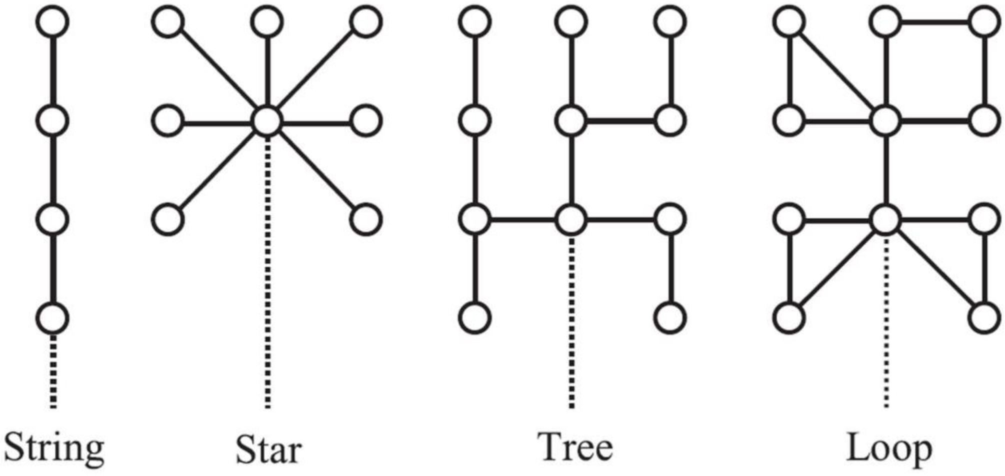


Figure 3.8: Common topologies for connecting wind turbine nodes (Smail et al., 2018)

3.2.2. Battery Energy Storage System

The primary applications of BESS can be categorised into three groups and 16 distinct types related to power supply, power grid, and power distribution (Figure 3.9). BESS significantly enhance schedule tracking as well as the integration and utilisation of new energy power generation (Li & Wang, 2021).

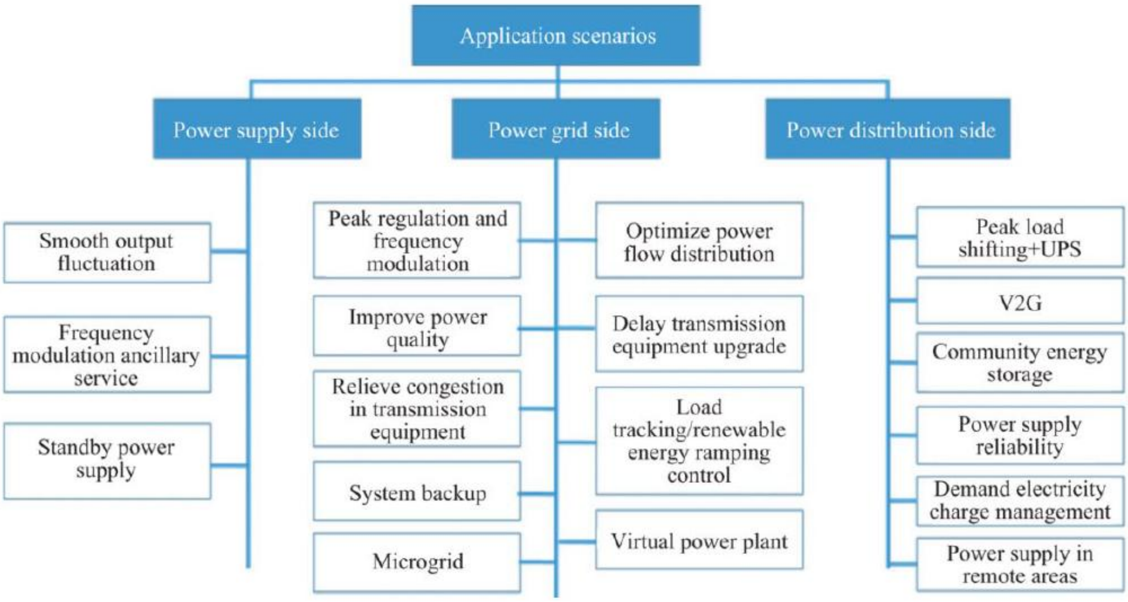


Figure 3.9: **Battery scenario applications** (Li & Wang, 2021)

Figure 3.9 depicts five typical power system services that BESS can provide.

Table 3.1: **BESS power system services categories** (Liu, 2022)

Category	Description
Bulk energy service	Electric energy time-shift (arbitrage) Avoided renewable curtailment Electric supply capacity
Ancillary services	Frequency regulation Spinning, non-spinning, and supplemental reserves Voltage support Black start Other related uses
Transmission infrastructure services	Transmission upgrade deferral Transmission congestion relief
Distribution infrastructure services	Distribution upgrade deferral Voltage support Outage mitigation
Customer energy management services	Power quality Power reliability Retail electric energy time-shift Demand charge management

Grid-connected energy storage systems also rely heavily on BESS, with lithium-ion batteries taking the lead owing to their better performance metrics. While other technologies have their uses, many fail to meet essential criteria like efficiency, operational complexity, or energy density. Examples of such technologies are lead-acid, sodium-sulfur (NaS), and redox flow batteries. Lead-acid batteries have a limited cycle life and a low energy density, but they are mature and inexpensive. Despite their excellent cycling life and energy density, NaS batteries aren't widely used because of their high operating temperatures. Although redox flow batteries are adaptable in terms of power and energy ratings, their poor efficiency and energy density render them unfit for use in demanding applications. The results of several electrochemical battery technologies are shown in Figure 3.11. (a) Flowable lead acid, (b) Sodium sulphur, (c) Lithium ion and (d) Radox Flow.

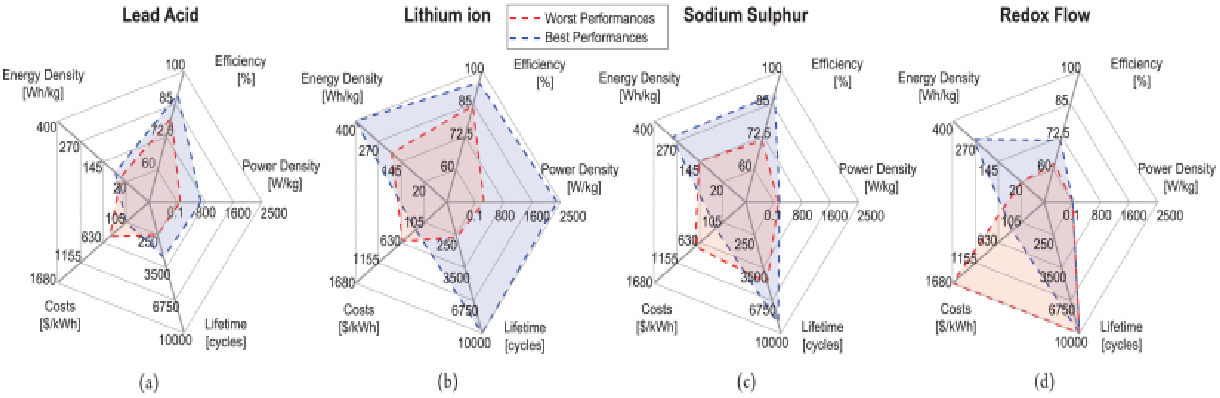


Figure 3.10: **BESS performances** (Stecca et al., 2020)

Lithium-ion batteries surpass these alternatives with high energy density (90–190 Wh/kg), excellent efficiency (up to 95%), and a long lifespan (up to 10,000 cycles, depending on the chemistry). Within lithium-ion chemistries, Lithium Nickel Manganese Cobalt (NMC) stands out as the optimal choice due to its balance of performance, cost, and lifespan. The declining costs of lithium-ion batteries, which dropped significantly from $650/kWh in 2013 to $156/kWh in 2019, further enhance their appeal for grid applications. The technology is widely used in electric vehicles and stationary storage, cementing its position as the industry standard for high-performance energy storage systems (Stecca et al., 2020). Figure 2.11 presents the price of a lithium-ion battery and its components over the past many years.

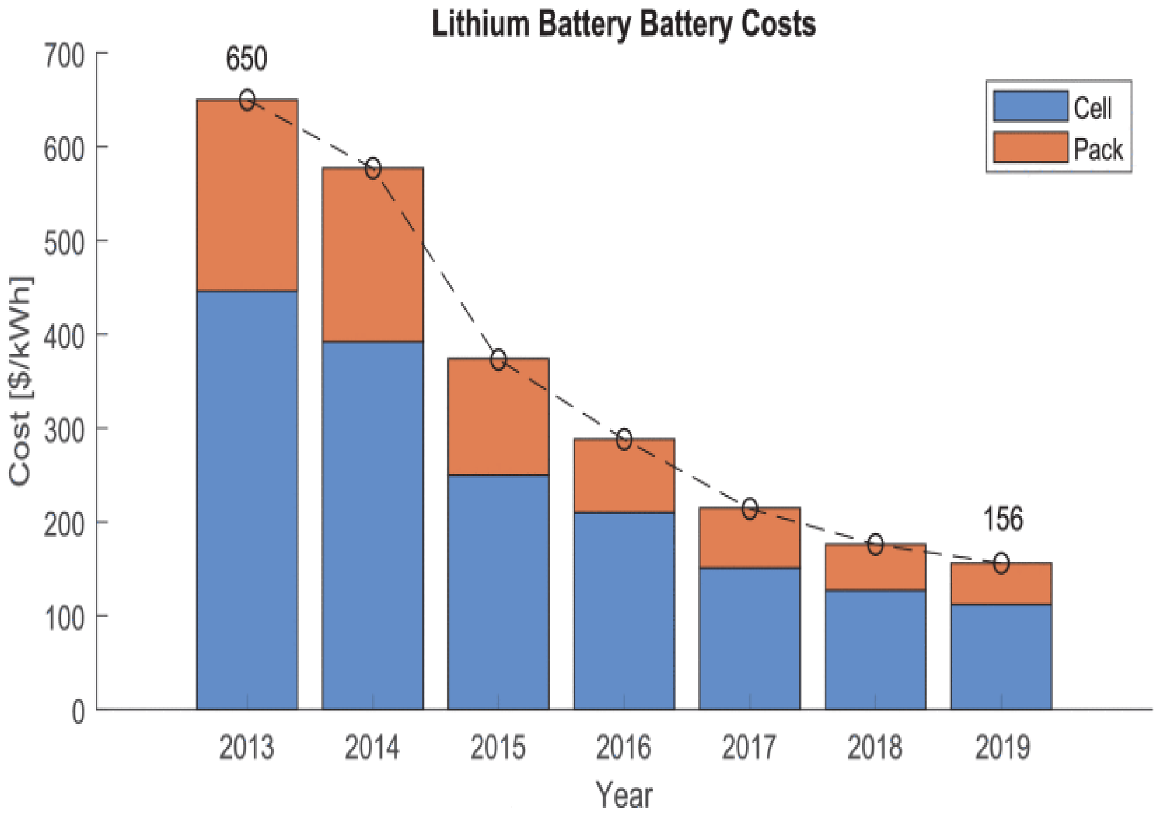


Figure 3.11: **The price of a lithium-ion battery and its components over the past many years** (Stecca et al., 2020)

Integrating lithium-ion batteries into grid systems requires efficient power electronics, particularly DC-AC converters, to connect storage systems to the AC grid. As the battery costs continue to decline, Power Conditioning Systems (PCS) will represent a larger share of total system costs, making their efficient design essential. By leveraging the advantages of lithium-ion batteries and addressing system integration challenges, energy storage systems can meet the growing demands of grid reliability and renewable energy integration, positioning lithium-ion batteries as a cornerstone of modern grid infrastructure (Stecca et al., 2020). Thus, this study research used lithium-ion batteries for wind integration with BESS.

3.2.3. Grid Code

A grid code establishes the technical and design requirements for integrating renewable energy, including wind power, into the electric grid. It specifies obligations for both wind farm operators and grid operators to ensure safe, reliable, and efficient power delivery (Nhlapo & Awodele, 2020).

Key necessities for grid codes:

- Customer (electricity user) requirements;
- Maintain voltage levels within safe operational ranges;

- Ensure instant power availability and frequency stability;
- Provide electricity at a reasonable cost;
- Wind farm operator requirements;
- Voltage at the connection point should remain within safe levels;
- Allow for the sale of generated electricity without curtailment;
- Ensure the reliability of the power system for continuous power export.

Grid codes are enforced by national regulatory authorities, such as the Swedish Energy Market Inspectorate or South Africa's energy regulatory bodies. In Europe, the Requirements for Generators (RfG) define the rules for connecting power-generating facilities to the grid, categorising facilities by capacity and connection voltage (Nhlapo & Awodele, 2020).

3.2.3.1. Renewable Power Plants Grid Code Requirements in South African

Renewable Power Plants (RPPs) in South Africa are required to adhere to grid codes that outline the bare minimum in terms of technical specifications and design to be permitted to connect to either the Transmission System (TS) or the Distribution System (DS). At the Point Of Connection (POC), an RPP which consists of one or more units functioning as a single power plant must fulfil these conditions (Nomandela et al., 2023).

RPP Categories:

- Category A: 0–1 MVA (connected to low voltage);
- Category B: 1–20 MVA;
- Category C: 20 MVA or higher.

Key requirements:

- RPPs must withstand voltage deviations under normal and fault conditions, minimising active power reduction;
- They must operate continuously within specified voltage ranges and provide voltage stability as required.

3.2.3.2. Fault Conditions and Voltage Ride-Through (VRT)

The South African grid code outlines specific operations for RPPs under fault conditions. Voltage ride-through requirements ensure that the RPP stays connected and supports the grid during disturbances (Sewchurran & Davidson, 2017).

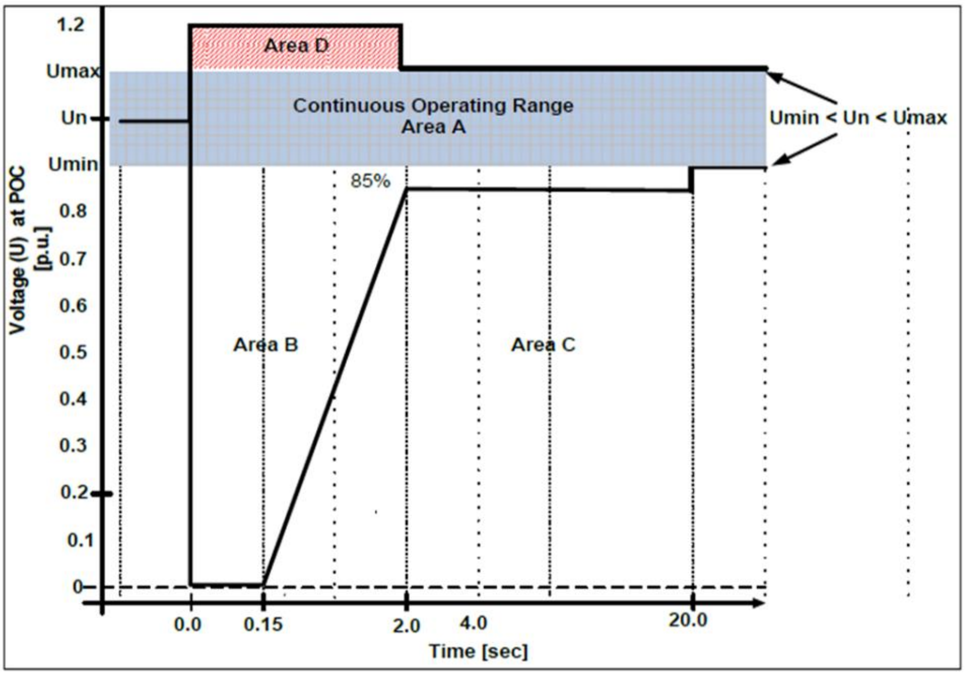


Figure 3.12: Voltage-time profile showing the voltage ride-through requirements for the wind generators (Nhlapo & Awodele, 2020)

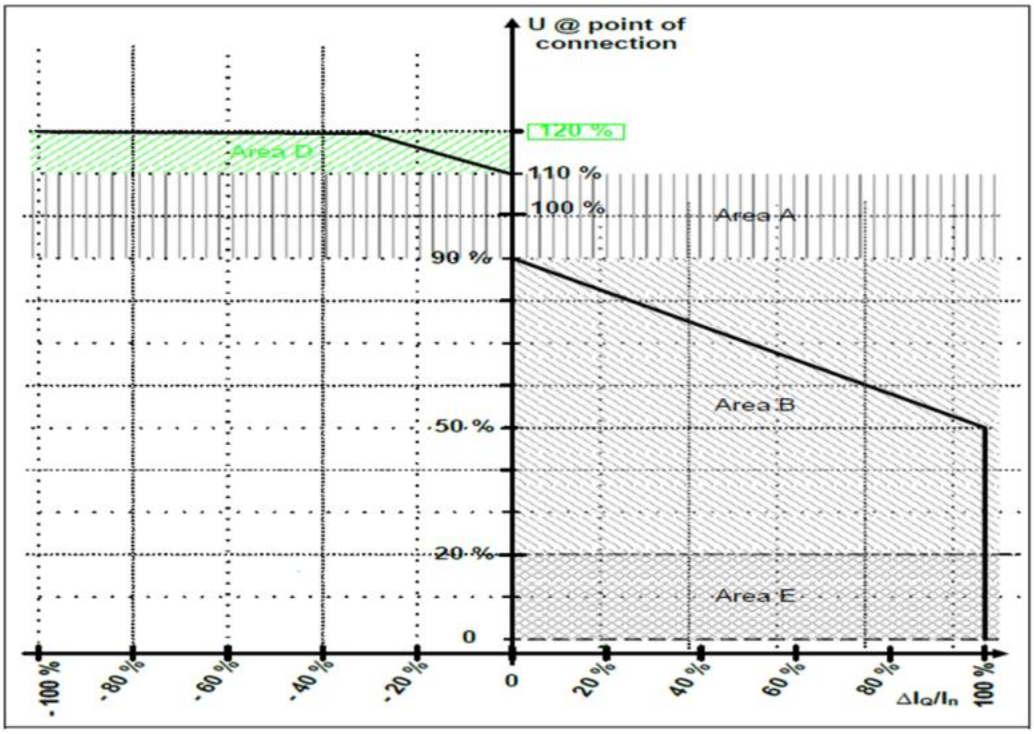


Figure 3.13: Reactive power support during voltage drops or peaks at the POC (Nhlapo & Awodele, 2020)

Voltage ride-through areas (Eskom, 2019):

- Area A: RPP remains connected with normal production.
- Area B: RPP supplies reactive power during voltage drops, maintaining grid stability. It must:
    - Withstand voltage drops to zero for 0.15 seconds without disconnecting;

  - Prioritise reactive power supply overactive power during voltage drops;
  - Maintain active power proportionally reduced to voltage drops below 85%;
  - Disable reactive current support on request by the operator.
- Area C: RPP disconnects when conditions exceed safe operational limits.
- Area D: RPP absorbs reactive power during voltage peaks, remaining connected and stable.
- Area E: RPP provides continuous reactive current support to stabilize voltage unless disconnection becomes necessary.

3.2.3.3. Reactive Power Capabilities and Voltage Control

RPPs must meet reactive power and voltage control requirements for steady-state operation. The grid code specifies the following:

Key requirements (Eskom, 2019):

- Reactive power modes: Voltage, power factor, or reactive power (Q or MVAr) control, with only one mode active at a time;
- Operating range: RPPs operating between 5% and 100% of rated active power must vary reactive power within specified limits (±0.33 p.u., corresponding to a power factor of 0.95 leading/lagging);
- Voltage dependency: Minimum and maximum reactive power support at the POC depends on voltage levels;
- For large-scale RPPs (Category C), these technical capabilities are critical for grid stability and efficient power integration.

Figure 3.14 highlights the relationship between reactive and active power at nominal voltage, showing the shaded operational region where RPP must maintain a power factor of 0.95 (leading and lagging) within ±0.33 p.u. of reactive power to support grid stability.

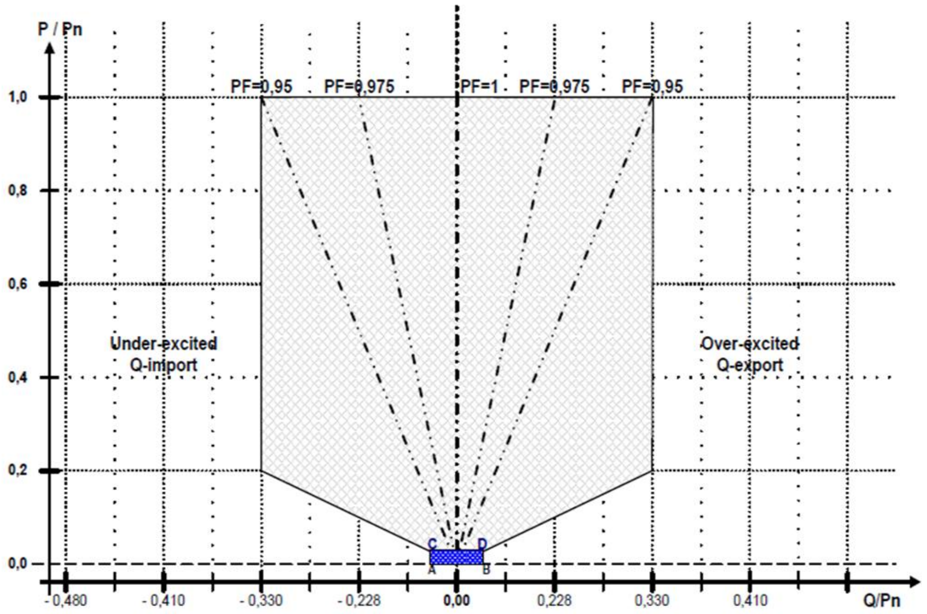


Figure 3.14: Reactive power requirements in relation to active power for Category C RPP at nominal voltage at the POC (Nhlapo & Awodele, 2020)

Figure 3.15 complements this by depicting the voltage-dependent reactive power control range, emphasising the need for RPPs to adapt the reactive power output (Qmin and Qmax) to maintain steady-state voltage stability under varying operational conditions. Together, these figures underscore the critical role of reactive power management in ensuring the reliable integration of large-scale renewable energy systems into the grid.

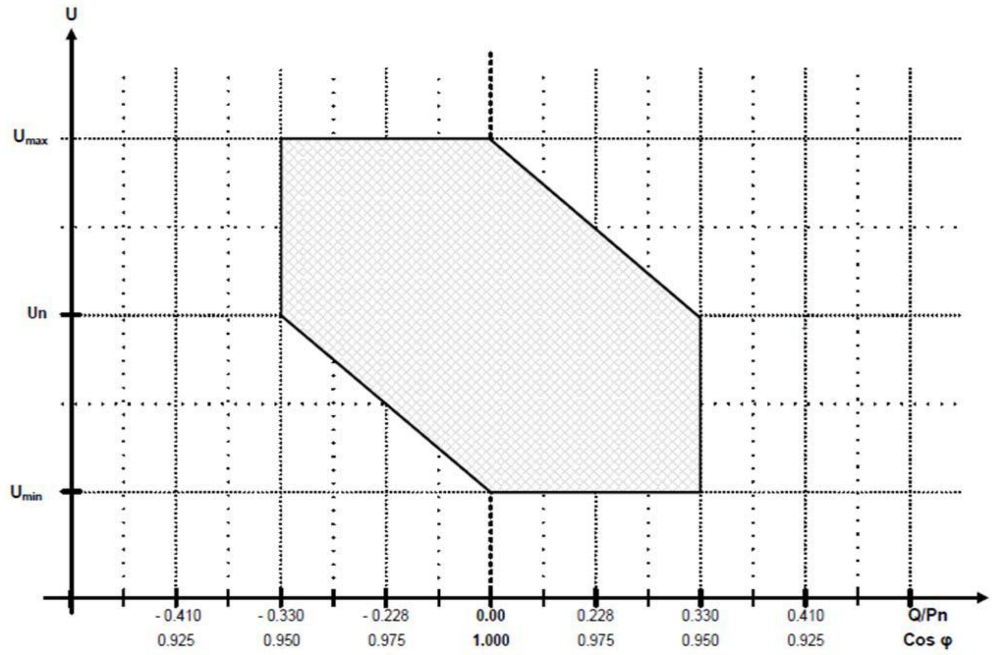


Figure 3.15: Reactive power requirements and voltage control range at the POC for Category C RPP (Nhlapo & Awodele, 2020)

This comprehensive framework highlights the alignment of South African grid codes with international best practices, ensuring that renewable energy plants like wind farms contribute effectively to a reliable and sustainable energy system.

3.2.4. Research Methodological Approach

The methodological approach that led to the research approach was promoted by the data collection from the Chaba Wind Farm, which is located in the Eastern Cape, north of East London town. The wind farm was commissioned in 2015 and the production data from the Commercial Operation Date (COD) was availed to be analysed. Also, a comparison was made to other EDF renewable fleets for concrete evidence and proper analysis of this data.

The research design and approach of this paper were used to determine the most suitable energy storage platform favouring all the technical evaluations, environment, and logistics of the components of the whole system integration, the lifespan of the plant, and the sizing of the BESS. The used approach was a mixed method of qualitative and quantitative methods. Developing a wind farm integrated BESS to mitigate the variability of power generation requires a systematic research approach (Yang et al., 2018). Here is a structured framework that is used for conducting such work:

- Literature review: Conduct a comprehensive review of existing literature on wind energy integration and BESS technologies. Identifying key studies, methodologies, and the findings related to mitigating wind power variability using energy storage systems to mitigate the observed variations (Beaudin et al., 2014).
- Wind resource assessment: Perform a detailed assessment of the wind resource at the proposed wind farm site/area and analyse historical wind data, including wind speed, direction, and variability, to understand the potential the power generation profile. This process is done over years (3-5) covering all the seasons and utilising proper environmental data analysis (Abdelrahman et al., 2022).
- BESS technology selection: Evaluate suitable different battery technologies for the grid-scale energy storage applications to be employed. Consider all factors such as energy density, efficiency, cycle life, response time, and cost (Gupta, 2015).
- Model development: There is a need to develop mathematical models to simulate the behaviour of the wind farm and the integration of the BESS system. These models should accurately represent the variability of wind power generation, and the response characteristics of the energy storage system brought to mitigate the simulated variations (Ciupăgeanu et al., 2019).
- Integration strategies: Investigate various integration strategies for combining wind energy and BESS to mitigate variability. This includes strategies for smoothing output fluctuations,

for optimising energy dispatch, and for providing grid ancillary services (Gwabavu, & Raji, 2021).

- Optimisation algorithms: The development of optimisation algorithms to optimise the operation of the integrated wind-BESS system was implemented together with the maintenance of the system (Al Shereiqi et al., 2020). These algorithms consider factors such as environmental forecasts, electricity market factors, chosen storage platform state of charge and discharge, and grid constraints factors to maximise economic benefits and grid stability elimination of the fluctuations in question (Li, & Wang, 2019).
- Control strategies: Design control strategies to manage the charging and discharging of the BESS in response to the changes in wind power output and grid conditions. Implement control algorithms that ensure optimal operation while meeting performance and safety requirements (de Siqueira et al., 2021).
- Performance evaluation: Conduct extensive simulations and/or real-world testing to evaluate the performance of the integrated system. Assess its ability to mitigate wind power and frequency variability, provide grid support services, as well as improve the overall system reliability and efficiency (Liu et al., 2024).
- Economic analysis: Perform a technological economic method to analyse and assess the cost-effective method of deploying the integrated system (Beltran et al., 2020). Consider all costs for the integration such as capital costs, operational costs, revenue streams, and potential savings from proposed curtailment and improved grid stability states (Lopez-Lorente et al., 2021).
- Risk assessment: Identify and evaluate potential risks associated with the development and deployment of the integrated system. Assess technical, financial, regulatory, and environmental risks, as well as develop mitigation strategies to address all these risks (Hannan et al., 2021).
- Validation and deployment: Upon the evaluation of factors patterning the deployment of this system integration, the validation of the performance and economic viability of the integrated system through pilot projects or demonstration sites and algorithm simulations is critical (Bhatnagar et al., 2013). Gather feedback from stakeholders, funders, and buyers. Refine the system design and operation based on real-world experience in eliminating or mitigating almost all the stipulated problems from the initial project implementation to be modified (Perez-DeLaMora et al., 2021).

By following this research approach, the researchers and practitioners can develop effective solutions for the integration of wind energy with battery energy storage systems to mitigate variability and enhance the overall performance and reliability of renewable energy systems.

3.2.5. Load Flow

A power system's generators, transmission lines, substations, and distribution systems are all part of the load flow analysis, which is a basic study of the system's steady-state performance. To solve for voltage magnitudes, angles at bus bars, and power flow on branches, the analysis employs iterative approaches, which are necessary because the interactions between system parts are not linear. Important covered details include voltages at nodes, fluxes of active and reactive power, effects of network augmentation, sizing of conductors, and the minimisation of system loss. Efficient power system planning and operation are made possible by load flow analysis, which also sets the stage for dynamic research.

A total of four parameters which are angle, voltage magnitude, actual power, and reactive power are associated with each bus in the network. According to these criteria, there are three distinct kinds of buses. The reactive power and voltage angles are unknown variables on generator buses, also known as voltage control buses, which have defined voltage magnitudes and power generation. By solving for the magnitude and angle of voltage, the load buses determine reactive and actual power. The slack bus (or swing/reference bus) balances the system, injecting or consuming power to achieve convergence, with its voltage angle and magnitude defined. Solving the load flow requires equations derived from the nodal admittance matrix, addressing these variables for all buses. Hence, the two unknown variables must be solved for each bus using two parallel equations (Equation 3-5 and 3-6), which are derived from the nodal admittance matrix (Equation 3-7).

$$\mathbf{0} = -\boldsymbol{P_k} + \boldsymbol{V_k}\sum_{\boldsymbol{a}=\mathbf{1}}^{\boldsymbol{N}} \boldsymbol{Y_{ka}}\boldsymbol{V_a}\,\mathbf{cos}(\boldsymbol{\delta_k} - \boldsymbol{\delta_a} - \boldsymbol{\delta_{ka}}) \quad (3\text{-}5)$$

$$\mathbf{0} = -\boldsymbol{Q_k} + \boldsymbol{V_k}\sum_{\boldsymbol{a}=\mathbf{1}}^{\boldsymbol{N}} \boldsymbol{Y_{ka}}\boldsymbol{V_a}\,\mathbf{sin}(\boldsymbol{\delta_k} - \boldsymbol{\delta_a} - \boldsymbol{\delta_{ka}}) \quad (3\text{-}6)$$

$$\boldsymbol{I_a} = \sum_{\boldsymbol{k}=\mathbf{1}}^{\boldsymbol{n}} \boldsymbol{Y_{ka}}\boldsymbol{V_a}\,, \quad \boldsymbol{n} = \mathbf{1}, \mathbf{2}, \dots, \boldsymbol{n} \quad (3\text{-}7)$$

In the above equations, P_k and Q_k denote the net active and reactive power injections at bus *k*, respectively. V_k and V_a represent the voltage magnitudes at buses *k* and *a*, while δ_k and δ_a are the corresponding voltage phase angles. Y_{ka} and δ_{ka} denote the magnitude and phase angle of the admittance between buses *k* and *a*. I_a is the injected current at bus *a*, and N is the total number of buses in the system.

A power system's steady-state voltage, current, and power conditions can be determined through load flow analysis, which serves as the basis for numerous operational evaluations. To ensure that protective devices are coordinated properly, and that the system remains stable, these steady-state circumstances give important initial values for three-phase fault analysis. This analysis compute’s fault currents, voltage drops, and system reactions during symmetrical failures. Typically, an imbalanced three-phase fault begins as a phase-earth fault. Important for high-speed protection is the fact that, even when a circuit breaker trips on a three-phase fault, the fault could occur in one phase first. The appropriate phasor diagram is displayed in Figure 3.6. The voltages to neutral are zero at the fault site. If the voltages to neutral before the fault were AN, BN, and CN, then the voltages at a location distant from the fault (such as a relay controlling a circuit breaker) are A′N, B′N, and C′N. The circumstances are unrelated to the system's earthing configurations in a symmetrical short-circuit.

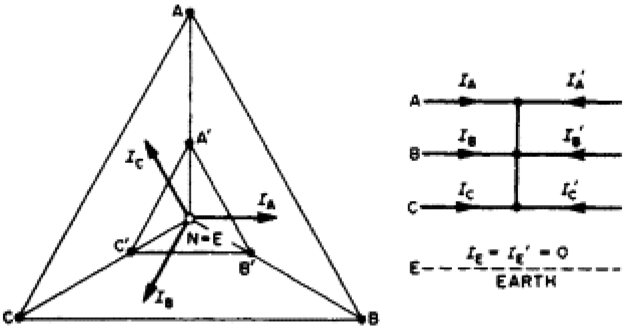


Figure 3.16: **Three-phase fault phasor diagram (AT Johns, 2003)**

3.2.6. DIgSILENT PowerFactory

DIgSILENT GmbH's PowerFactory, hereinafter referred to as PowerFactory, is a tool for simulating power systems. Industrial electrical power networks, including generation, transmission, and distribution, can be modelled using PowerFactory. It includes a number of tools for analysing power systems, including those for transmission and distribution networks, as well as load flow, short-circuit, quasi-dynamic, Root Mean Square (RMS), Electromagnetic Transients (EMT), economic, and other related features. The software also comes with DIgSILENT Programming Language (DPL) pre-installed, so users can automate simulations by creating or utilising existing scripts. In addition, PowerFactory is accessible and executable using Python scripts, which unlock a plethora of data analysis possibilities linked to this high-level programming language (DIgSILENT, 2021).

3.3. Methodological Approach

3.3.1. Description of the Wind Farm and BESS Models

A Power Management System (PMS), wind farm, BESS, converter, and wind power all work together to form the wind/BESS hybrid system. A transmission line connects the system to the main grid. The BESS is connected to the grid and the converter controls electricity charging and discharging at the Point of Common Connection (PCC). This method is useful for reducing the impact of wind power variability. With this integration, the wind/BESS hybrid system can be dispatched in the same way as traditional thermal power plants, greatly improving the wind farm's dispatchability. Thus, the desired dispatch order can be executed within the dispatching period, and the battery life can be extended simultaneously. For the layperson, the output of the wind/BESS hybrid system aims to mimic the desired dispatch curve PD as closely as possible, especially when battery charging and discharging are minimal. If this method is utilised successfully, it reduces or gets rid of variability in power generation (Wang et al., 2020).

The operation of the wind turbines that make up a wind farm is defined by two guiding principles: To harness the mechanical energy of moving air, a combination of an aerodynamic rotor blade and mechanical power control is employed, which is step one. The second step is the generation of electricity, which involves transforming mechanical energy into electrical energy using a generator, a step-up transformer, RMUs, a substation, and finally, a 132KV transformer (Knopper & Ollson, 2011). After that, the power network receives the electrical power and distributes it. The wind farm is integrated with a battery energy storage system to guarantee consistent and uninterrupted energy supply (He et al., 2022). As the need to lessen the world's impact on the environment has been recognised on a global scale, several countries have made strides in incorporating renewable energy sources into their power grids to generate electricity for users. Electrical energy storage devices are crucial for microgrids that rely on renewable energy sources for electrical power generation (López González et al., 2015).

When demand is low, the BESS stores excess energy from the wind farm and releases it when demand is high, acting as a buffer. This feature guarantees a more consistent power supply by dealing with the intermittent nature of wind energy. Combining the wind farm with the battery energy storage system not only makes the energy supply more reliable, but it also opens up new avenues for making money. The wind farms that have integrated storage can participate in ancillary markets and earn more money by helping grid operators with things like voltage support and frequency adjustment (Ademulegun et al., 2020).

This feature helps to make the wind farms more financially viable and speeds up the transition to a greener energy system. Additional benefits such as reducing the inconsistency and unpredictability of renewable energy supply, can be achieved by incorporating a battery energy storage system into a wind farm. The uncertainty of wind patterns, which can cause power production swings, is one of the main challenges to integrating wind power into electrical networks. However, this problem can now be effectively addressed by combining renewable energy sources with battery energy storage systems, thanks to developments in battery technology (Kordkheili et al., 2021). While this integration model's development and construction costs are high, the model's operations are beneficial to both consumers and businesses. Compared to other parts of the world, this structure is extremely complicated, yet it has a good chance of succeeding.

3.3.2. Explanation of the Integration Process

Power generation from Wind Turbines (WP) has recently attracted significant interest worldwide. Worldwide, demonstration projects for wind-battery energy storage systems and gearbox joints are being built in regions ideal for this configuration. To improve the power quality of hybrid wind power systems, a battery energy storage system provides flexible energy management. To reduce the impact of wind power fluctuations or enhance power quality, numerous projects and developments have suggested various control strategies and configurations for hybrid energy storage systems (Ahmed et al., 2024). These systems include battery energy storage, Superconducting Magnetic Energy Systems (SMES), Flywheel Energy Systems (FES), Energy Capacitor Systems (ECS), and fuel cell/electrolyser hybrid systems. Where the integration can support either wind or PV systems, the utilisation of batteries in wind/BESS hybrid power generation systems has begun to serve multiple purposes. These include, but are not limited to, smoothing wind and solar energy, improving reliability, stabilising the grid, reducing gearbox losses and congestion, and providing grid services and electric vehicle charging stations (Hannan et al., 2022).

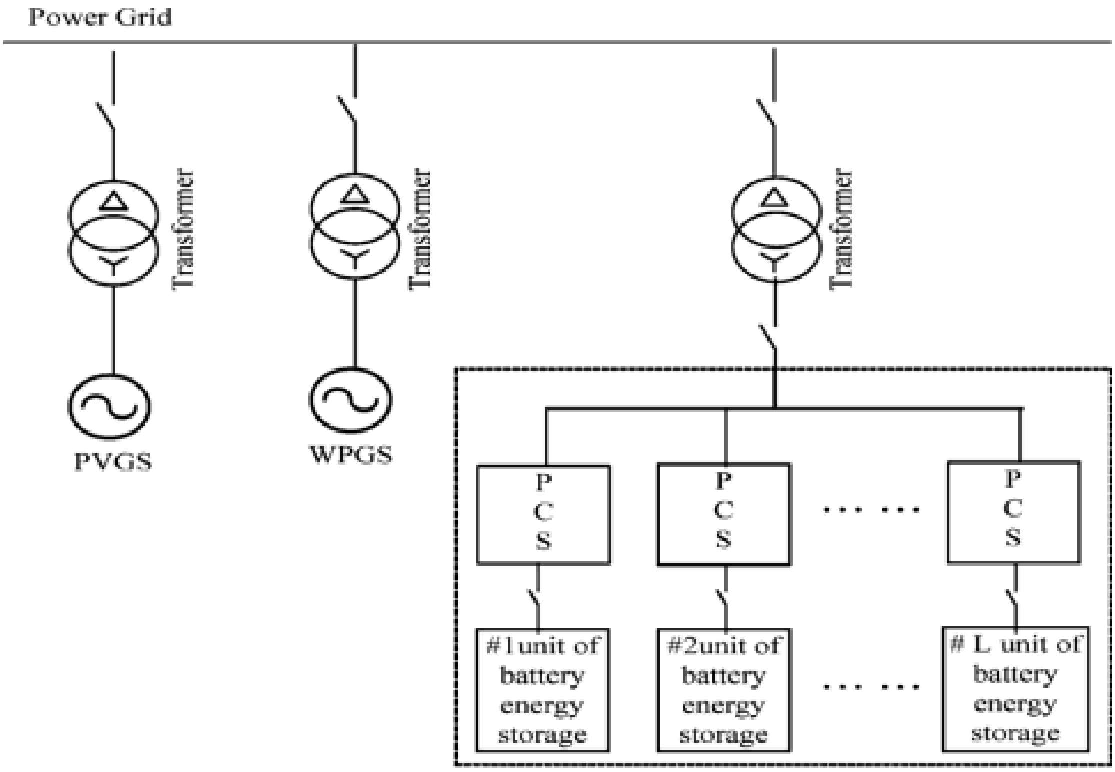


Figure 3.17: Wind/BESS hybrid power generation system (Li, Yao, & Hui, 2016)

How to handle power fluctuations in renewable energy sources, especially wind power generation, is currently a hot topic. A new issue has arisen with the installation of an energy storage system such as BESS, even if an earlier one has been resolved. According to Liang (2016), when using BESS to control wind power variations, a balance needs to be found between battery utilisation and smoothness. That is to say, the battery can conserve power if the result is not too critical. Despite the abundance of effective BESS-based methods for reducing power fluctuations in renewable energy systems, no clear smoothing targets have been defined for the wind and solar farms that are connected to the grid (Lamsal et al., 2019). For smoothing control purposes, the use of power fluctuation rate limitations has received scant attention in these systems. The publication's control approaches failed to address the distribution of power among numerous BESS, instead concentrating on smoothing with small-scale BESS. Appropriate and economical control strategies for large-scale BESS are still desperately needed (Barra et al., 2021).

3.3.3. Parameters Considered for Analysis

The sizing and optimisation of battery energy storage systems for wind power plants in a distribution grid requires strictly calculated parameters for analysis. This goes from the actual wind farm output (M) to BESS storage and output (MWh), the initial determination of necessary BESS capacity and the assessment of power flow. Identify the ideal location and necessary capacity of BESS (MW & MWh) to maximise the benefits for the specific use case(s) while considering the physical space and limitations of the local network. Perform power evacuation, rapid voltage change, load rejection tests, fault level studies, and charging requirements to verify technical compliance with the BESS (Anon, 2020). The BESS storage model and the parameters for analysis include evaluating the suitability of the storage capacity, simulating storage operation scenarios (charging/discharging rate), modelling storage features (e.g. degradation factors like efficiency, auxiliary power, cycle life, etc.), the parameters for storage and the profile of BESS output As well as the duty cycle for the battery energy storage system throughout one full year according to the specific use case(s) (Kucevic et al., 2020.

The distance from the primary production site to the commercial substation is an important factor that grid connection and grid code compliance will take into consideration when determining the transmission power quality. To maintain stability, it is necessary to carefully anticipate the maximum unpredictability, which can cause oscillations that could damage the system. For controllers to become more dynamic, real-time uncertainty assessments are essential. The influence of battery health on power distribution strategies was not considered by Jannati and Foroutan (2020), who created a heuristic-based control for BESS-based short-term wind power smoothing. To regulate energy variations and wind power, Altin and Eyimaya

(2018) developed a controller using a first-order low-pass filter. According to Jannati and Foroutan's (2020) research, power smoothing with BESS could be compromised if the cut-off frequency is not properly selected. Reducing power fluctuation was the objective of the methodology. It did not, however, consider one of the fundamental parameters which is the batteries' health and how it affects the power allocation strategies.

Integrating wind energy with BESS necessitates meticulous examination to guarantee the utmost efficiency, dependability, and financial feasibility. Detailed several parameters are considered during this analysis:

- **Wind resource assessment**: Comprehending the wind resource at the project location holds significant importance. Factors such as wind speed, directionality, and turbulence intensity play a crucial role in predicting the potential energy production of the wind farm (Murthy, & Rahi, 2017).
- **Energy production profile**: The evaluation of the fluctuation and irregularity in wind energy generation over a period is fundamental (Atia, & Yamada, 2016). This incorporates the examination of daily and seasonal trends, along with the occurrence of exceptional phenomena like sudden wind surges and calm periods.
- **BESS capacity sizing**: Estimating the most suitable capacity for the battery energy storage system entails a thorough analysis of the wind energy production profile and load demand trends (Yang et al., 2018). The BESS capacity must be adequate to store surplus energy during high wind generation phases and release it during low wind periods or periods of high demand (Rekioua, 2023).
- **Charge and discharge rate**: Understanding the charge and discharge rate of BESS is critical to match the changing nature of wind power generation (Abhinav, & Pindoriya, 2016). Fast response times are needed to smooth out fluctuations in wind power and maintain grid stability (Barra et al., 2021).
- **State management**: The effective management of the State-of-Charge (SoC) of a BESS is essential to maximise its performance and lifetime (Jamroen, 2022). This requires the implementation of control strategies to ensure that the BESS operates within optimal SoC ranges responding to grid signals and wind power fluctuations (de Siqueira et al., 2021).
- **Grid integration requirements**: Compliance with grid integration standards and regulations is essential to ensure smooth integration of wind energy and BESS into the existing power system (Fotis et al., 2022). This includes things like voltage and frequency regulation, network codes, and network connection requirements.
- **Economic analysis**: Conducting a thorough economic analysis is crucial in evaluating the profitability of integrating wind energy with BESS. This includes an assessment of capital costs, operation, and maintenance costs, revenue streams such as energy arbitrage,

ancillary services, and capacity markets, as well as savings from network support services (Rotella Junior et al., 2021).

- **Techno-economic optimisation**: Optimising the size, operation, and control strategies of an integrated wind and BESS system to minimise total costs and maximise benefits is essential (Liu et al., 2020). This may require the use of advanced modelling techniques such as techno-economic optimisation algorithms to find the optimal configuration and operating schedule (Cuisinier et al., 2021).
- **Environmental impacts**: The assessment of the environmental impacts of an integrated wind and BESS system, including factors such as land use, wildlife, and life cycle emissions, is essential to ensure sustainability and regulatory compliance (Hannan et al., 2021).
- **Risk analysis**: Identifying and mitigating risks associated with wind energy and BESS integration, such as technical risks, market risks, and political/regulatory risks, is essential to the success and long-term viability of the project (Marsters et al., 2021).

By considering these parameters comprehensively, the developers and operators can design and implement integrated wind and BESS systems that are efficient, reliable, and economically viable.

3.3.4. Data Collection Methods

Firstly, the data collection methods cover how a wind farm development starts operations, and then the data for the chosen running site, which the research paper is based on, is discussed. The development studies for a wind farm always detail the forecast covering all seasons; for three to five years. Forecast data is collected for wind profiles; after this period, it is then concluded on the expected production based on the preferred platform to be installed in the area chosen. This also shows high wind seasons and low wind seasons for the chosen site. The study helps to detail the needed platform, from design, durability, cost implications, and business possibilities. From these numbers, a BESS sizing is then concluded. Moreover, the collected data can then be simulated in any simulation tool, putting into practice the system to be built, and if there are any modifications required, then additional parameters will be simulated and can be implemented prior to the physical site construction of the project.

In this research paper, the data for annual production for the Chaba wind farm was collected for seven years, and to have strong, reputable results, another two neighbouring sites were used as reference points for the issue in question. Three-year actual production is discussed and compared to expected three-year production from the installed capacity. The analysis then points out production loss each year and the loss seasons where the use of BESS can be employed to overcome the issue. Table 3.1 shows three wind farms on one cluster. Their performance from 2016 to 2022 is highlighted under actual production, and a comparison against expected production from installed capacity is done under expected production; and the measurements are in KWh. Here it is seen that the installed capacity expected production is much higher than the actual production. The factors of this difference are weather conditions, breakdowns, maintenance schedules, environmental and utility curtailments.

Table 3.2: Actual production versus expected production

	Actual Production (MWh)			Expected Production (MWh)		
YEAR	**Grassridge WF**	**Chaba WF**	**Waainek WF**	**Grassridge WF**	**Chaba WF**	**Waainek WF**
2016	177,006.308	57,755.364	94,426.994	518400	181440	207360
2017	171,057.888	58,298.190	95,641.611	518400	181440	207360
2018	164,323.676	59,884.137	92,581.042	518400	181440	207360
2019	180,161.435	59,670.604	96,628.319	518400	181440	207360
2020	173,732.970	57,886.237	94,654.991	518400	181440	207360
2021	170,712.654	59,013.642	91,929.515	518400	181440	207360
2022	162,373.828	56,700.893	90,259.972	518400	181440	207360
total	**1199368.759**	**409209.067**	**656122.444**	**3628800**	**1270080**	**1451520**

Furthermore, Table 3.2 notes the lost production from the expected column against the actual production is highlighted where the lost production is a difference of actual and expected production. The lost production in each site is more than 50% of the expected production. This phenomenon states a lot about the plant efficiency status ranging from 3% - 45% on average in seven years.

Table 3.3: Lost production versus efficiency of the plant

Lost Production (MWh)			efficiency of plant		
Grassridge WF	**Chaba WF**	**Waainek WF**	**Grassridge WF**	**Chaba WF**	**Waainek WF**
341,393.692	123,684.636	112,933.006	34%	32%	46%
347,342.112	123,141.810	111,718.389	33%	32%	46%
354,076.324	121,555.863	114,778.958	32%	33%	45%
338,238.565	121,769.396	110,731.681	35%	33%	47%
344,667.030	123,553.763	112,705.009	34%	32%	46%
347,687.346	122,426.358	115,430.485	33%	33%	44%
356,026.172	124,739.107	117,100.028	31%	31%	44%
2429431.241	**860870.933**	**795397.556**	**33%**	**32%**	**45%**

Chaba Wind Farm's monthly wind profile displays favourable months and less favourable months in terms of wind availability. The integration is based on these numbers to uplift the monthly production of the wind farm.

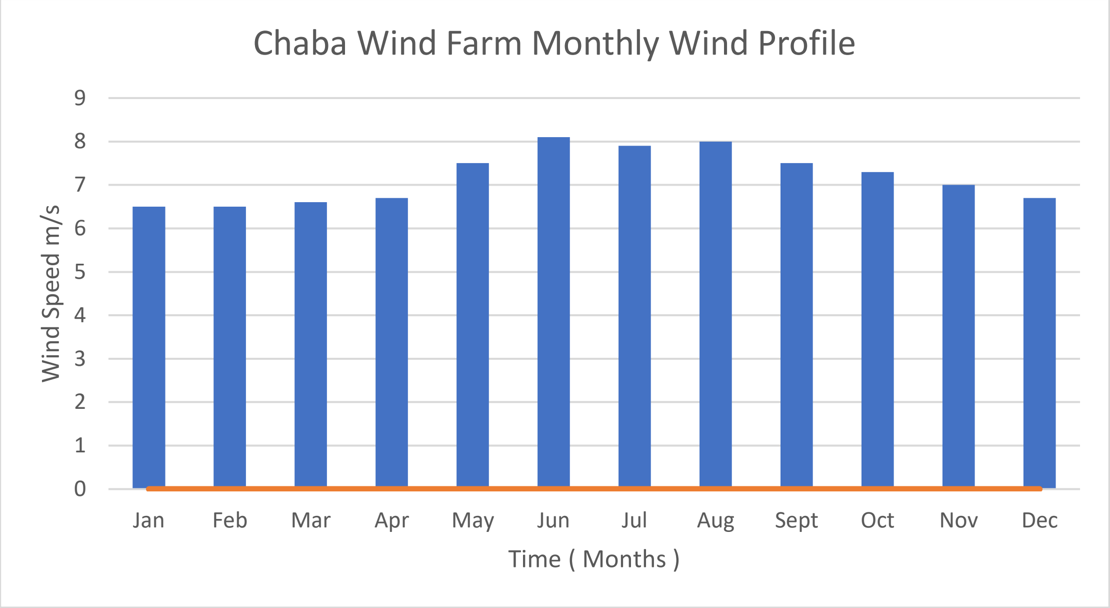


Figure 3.18: **Chaba Wind Farm monthly wind profile.**

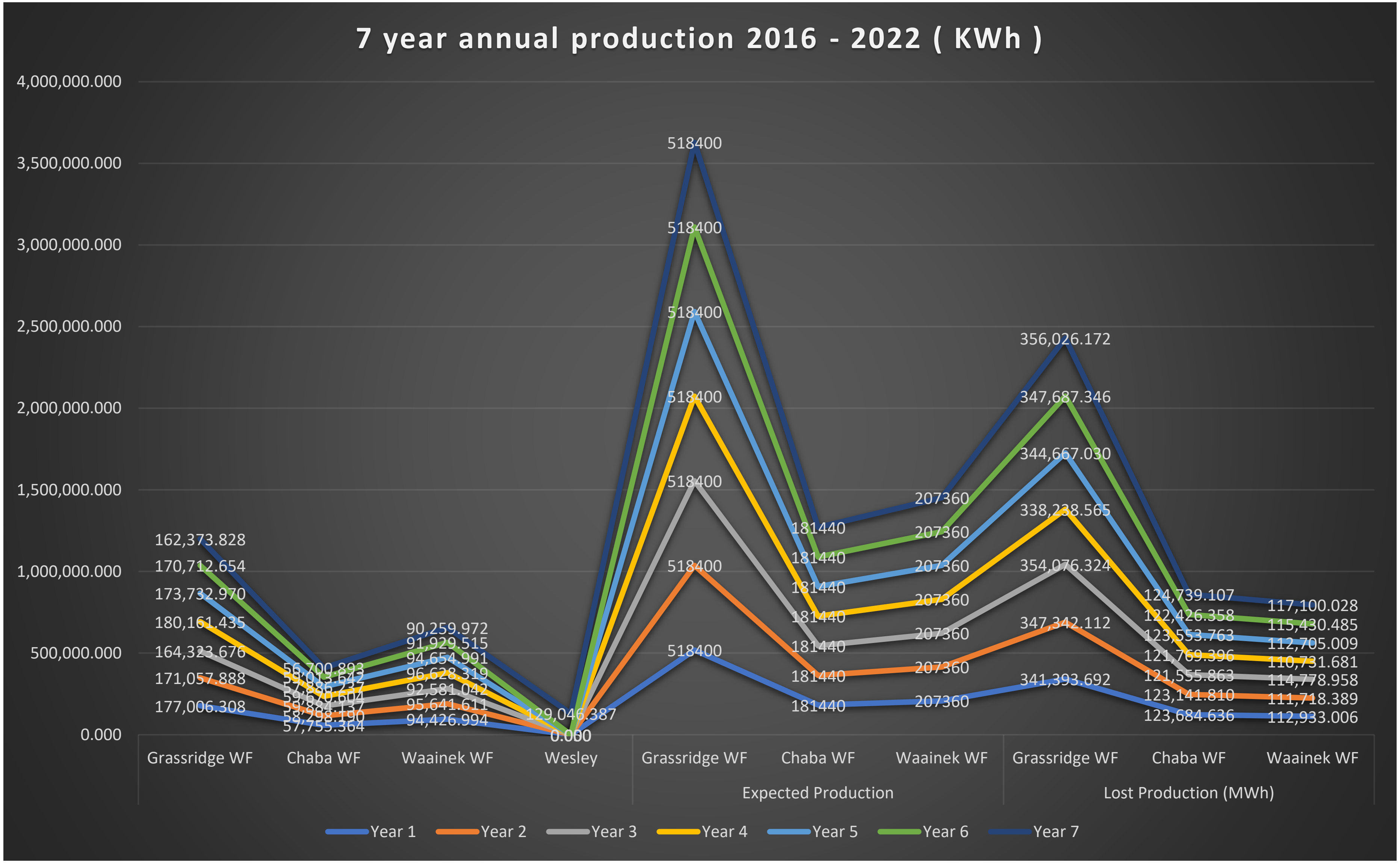


Figure 3.19: Seven-year annual production 2016 – 2017 (KWh)

Figure 3.19 presents a graph that shows the trends of the plant performance over seven years, and the data is extracted from the Vestas Online Business (VOB) client. This is a SCADA system that is used to monitor the plant and retrieve the history operations of the plant with all events logs.

3.3.5. Simulation or Experimental Setup

Time domain simulations in RMS and EMT modes, as well as frequency domain analysis, are conducted in DIgSILENT PowerFactory 2024 SP. The benchmark test system was designed for both Electromagnetic Transient (EMT) and Root Mean Square (RMS) modes. These models offer different levels of detail and suitability for various simulation objectives. Table 3.3 presents a comprehensive comparison between the two models, highlighting key characteristics and capabilities.

Table 3.4: **Comparison of the EMT and RMS models of the benchmark test system**

Feature	EMT Model	RMS Model
Grid	Differential equations	Algebraic equations
Converter	Controlled voltage source	Controlled voltage source
Separated Pos. and Neg. sequence control	No, only full space vector considered	No, only positive sequence is considered
Saturation of transformers and inductors	Can be activated/deactivated	Not represented
Common mode signal	No, but it can be implemented	No, but can be represented
Limitation of modulation index	Limited to one	Limited to one
Converter blocking	Possible, but converter control is not adapted	Possible, but converter control is not adapted
DC circuit and chopper	Represented	Represented
Measurement Filters	No	No
PLL	Represented	Represented
Voltage control (voltage support)	Direct proportional control without deadband	Direct proportional control without deadband
Generation of harmonics	No generation of harmonics through converters	50 Hz fundamental models
Integration step size	0.01 – 8 ms	5 – 200 ms
Possible disturbances	Any balanced and unbalanced grid faults, but converter controls only the full space vector	Only balanced faults (Positive Sequence)

EMT and RMS models have been implemented in DIgSILENT PowerFactory version 2024 SP. The implementation provides a robust platform for comparing these models' dynamic response and suitability for analysing various grid conditions and control strategies. The differences outlined in Table 3.3 highlight how each model aligns with specific simulation needs, such as high-fidelity transient analysis or steady-state grid stability studies.

3.3.6. Simulation Assessments

The simulation and assessment of the combined BESS and wind energy system was conducted to evaluate its capacity to mitigate power fluctuations, examine its financial and ecological influences, and authenticate the simulation outcomes through comparison with actual data. Simulation models are devised to accurately depict the behaviour of the wind farm and the integration of the BESS system. These models consider various factors, including wind speed, turbine characteristics, energy storage capabilities, and grid connection specifications (Vasudevan et al., 2021). The simulation models rely on mathematical and statistical algorithms and the data acquired from actual wind farms and BESS installations. Once the simulation models are developed, the subsequent stage involves verifying the precision and dependability of the simulation results by comparing them to real-world data (Kang et al., 2022). The simulation setup was of the wind farm with seven WTGs and a battery bank controlled by BMS. BESS was charged by the access energy produced during high winds and later used when the winds did not favour production. DigSilent was used in this simulation.

3.4. Summary

The chapter outlined the critical factors for successful integration, including wind resource assessment, BESS technology evaluation, and grid integration. Regulatory considerations, such as the compliance with grid codes and environmental impacts, were also examined to align with sustainability goals. This chapter established a robust methodological foundation for evaluating wind energy systems integrated with BESS by integrating theoretical insights and contributing to reliable and sustainable energy solutions. The key parameters for analysis include wind speed variability, BESS capacity, charge-discharge rates, and grid integration. The chapter also emphasised the technical and regulatory requirements of integrating renewable energy with the national grid. Load flow and fault analysis ensure operational stability and efficiency, while load assessments evaluate the -effectiveness of the proposed integration. By combining theoretical modelling, real-world data, and simulation-based validation, this research aimed to develop a robust system modelling for enhancing the reliability and sustainability of wind energy systems integrated with BESS.

CHAPTER FOUR

SYSTEM MODELLING AND SIMULATION

4.1. Introduction

The wind energy's inherent variability and intermittency present considerable challenges to grid stability, power quality, and reliability (Mathew, 2007; Nazir et al., 2022). This chapter examines the modelling and simulation of the Chaba Wind Farm, augmented by a lithium-based BESS, to address these challenges and guarantee reliable energy provision. The chapter begins by developing and delineating an extensive model that encapsulates the dynamics of wind turbines and wind field phenomena, encompassing turbulence, power variability, BESS, and grid integration. The BESS integration enhances wind power generation by storing surplus energy during peak production and providing power during low wind periods. This method not only alleviates intermittency but also improves the dispatchability of wind energy, increasing its compatibility with grid demands.

A series of simulations assesses the system's performance under various operating conditions, including steady-state operations, transient events, and fault scenarios. Scenarios, including initial system operation, load trips, and three-phase faults, are examined to evaluate the resilience and efficacy of the integrated wind farm and battery energy storage system. The model incorporates advanced control strategies such as voltage stabilisation, frequency regulation, and synthetic inertia response to ensure seamless grid interaction and reliability. This chapter illustrates how the Chaba Wind Farm and its BESS can deliver dependable, high-quality power and enhance grid stability using tools such as DIgSILENT PowerFactory. The insights derived from these simulations enhance the comprehension of renewable energy integration, providing a scalable framework for forthcoming wind farm initiatives. The chapter concludes by comparing the simulation results to existing literature, emphasising the technical and practical importance of the proposed solution.

4.2. Development of System Modelling and Simulation

Developing large wind farm models for simulation and control design presents considerable challenges, especially regarding computational capacity and simulation duration, which escalate with the number of turbines and model intricacy. The selection of numerical solvers, including implicit or explicit methods with fixed or variable step sizes, profoundly influences simulation speed, particularly for stiff systems; however, judicious selection of model components can alleviate these challenges (Chalikosa et al., 2022).

4.2.1. Wind Farm

The wind farm model consists of two primary subsystems: the wind turbine and the wind field. The wind turbine sub-system is engineered to enhance simulation efficiency while incorporating essential structural modes, including the primary blade, tower, and drivetrain modes. Every turbine model incorporates a comprehensive envelope controller to simulate authentic load dynamics and connects with a wind farm controller for power set-point modifications. The wind-field sub-system captures long-range correlations, encompassing low-frequency turbulence and wake effects, while incorporating high-frequency components locally for each turbine to optimise accuracy and computational efficiency. Figure 4.1 depicts a wind farm power plant.

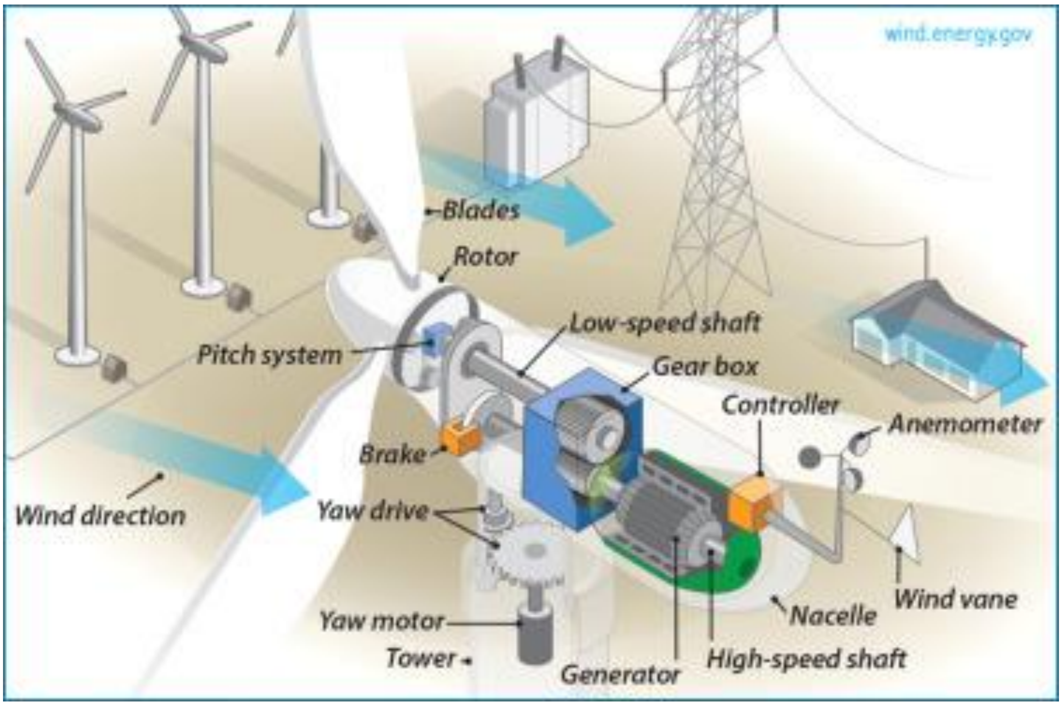


Figure 4.1: **Wind farm power plant (Action Renewable, 2019)**

The wind-field model generates a longitudinal and lateral turbulence time series using the Shinozuka cross-spectral density function algorithm, adapted from Veer's method (Shinozuka & Jan 1972). The power spectral density functions are represented by the diagonal elements of the $N \times N$ spectral density matrix, $S(f)$, which is produced by this method. The off-diagonal components, on the other hand, are cross-spectral density functions that show consistency between wind speeds at different turbine positions. Using IEC-recommended decay parameters, the coherence function considers mean wind speed, frequency, and geographical separation (Segarra et al., 2016). The Kaimal spectrum produces power spectral densities for turbulence components, with the spectral factorisation of $S(f)$ resulting in the frequency response matrix $H(f)$ (Kaimal et al., 1972). Correlated wind speeds are generated by applying $H(f)$ to random white noise inputs, with the resultant turbulent wind speed time series obtained through inverse Fourier transforms. The time series are retained within the simulation environment for integration with control algorithms, offering a computationally efficient and physically accurate model for wind farm operations (Kareem, 2008; Kareem, 1987). The turbulence time series can be generated using a 2D grid architecture, as seen in Figure 4.2.

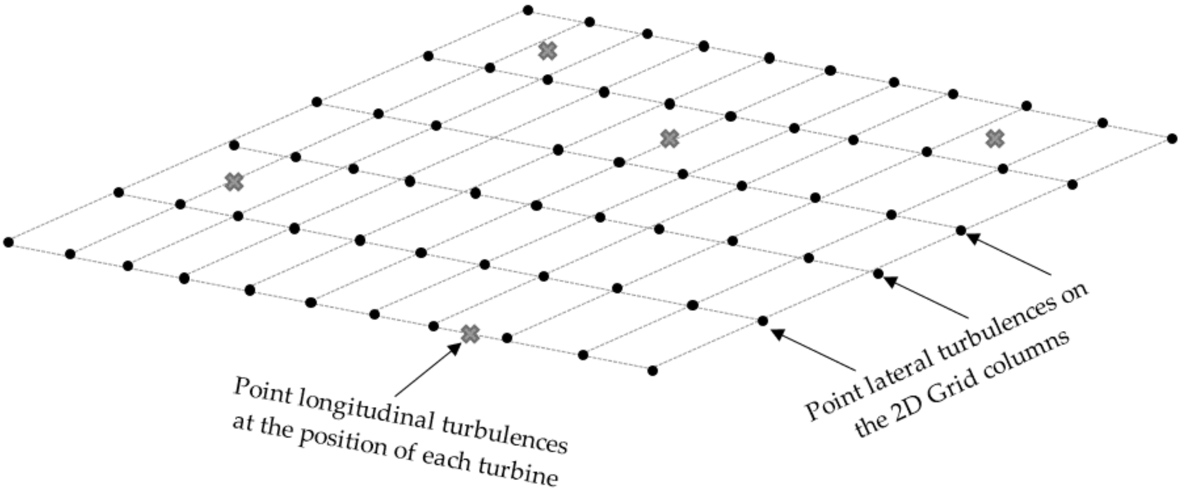


Figure 4.2: **Turbulence time series 2D grid layout (Poushpas, 2016)**

According to Poushpas (2016), the cross-spectral densities between two places A and B, are separated by a distance l:

$$\text{Coh}_{A,B}(f, l, U_0) = e^{-c_{u,v}\frac{fl}{U_0}} \qquad (4\text{-}1)$$

In which U_0 is the mean wind speed, l is the distance between points A and B, and f is the frequency in rad/sec. The cross-spectral density function's magnitude is:

$$\left|S_{A,B}(f)\right| = \text{Coh}_{A,B}(f, l, U_0)\sqrt{S_{AA}(f) \cdot S_{BB}(f)} \qquad (4\text{-}2)$$

The IEC recommends $c_u = 7.1$ and $c_v = 4.2$. as the coherence parameter decay factors for longitudinal and lateral separation, respectively. Discrete frequency domains are used in numerical computations and are defined as:

$$\Delta f = \frac{2\pi}{n \times \text{Sampling Time}} \qquad (4\text{-}3)$$

$$f = -n\Delta f : \Delta f : (n-1)\Delta f \qquad (4\text{-}4)$$

where n is the length of simulation time, Δf is the sampling frequency and f is the frequency in rad/sec. The PSDs are generated using the double-sided Kaimal spectrum as follows:

$$s_{u,v}(f) = \frac{1}{3}\frac{\sigma_{u,v}^2 L_{u,v}}{U_0\left(1+\frac{fL_{u,v}}{U_0}\right)^{5/3}} \qquad (4\text{-}5)$$

The longitudinal component u is equal to $\sigma_u = T_i\left(\frac{3}{4}U_0 + 5.6\right)$, the lateral component v is equal to $\sigma_v = 0.8\sigma_u$, the turbulence intensity (T_i) is denoted by L_u= 340.2, and L_v= 113.4. After that, the matrix $S(f)$ representing the spectral density function is factorised spectrally, and the following matrix $H(f)$ is calculated:

$$H_{11} = S_{11}^{1/2} \tag{4-6}$$

$$H_{21} = \frac{S_{21}}{H_{11}} \tag{4-7}$$

$$H_{22} = (S_{22} - H_{21}^2)^{1/2} \tag{4-8}$$

$$H_{m,k} = \frac{S_{m,k} - \sum_{l=1}^{k-1} H_{m,l}H_{k,l}}{H_{kk}} \tag{4-9}$$

$$H_{kk} = \left(S_{kk} - \sum_{l=1}^{k-1} H_{k,l}^2\right)^{1/2} \tag{4-10}$$

Where $m = 1,2,\ldots,N,\quad k = 1,2,\ldots,N,$ and N is the number of turbines.
The periodicity condition is:

$$S_{i,j}(f) = S(N+1{:}\,2N) + S(1{:}\,N), \quad i,j = 1,2,\ldots,\text{number of turbines} \tag{4-11}$$

N independent correlated point wind speeds with the necessary spectral features are obtained by using the H matrix as a frequency response function matrix with an input vector of N independent white noises. To get the $X(f)$ vector, one must:

$$w(t) = \frac{\text{randn}(1,\text{simulation time})}{\sqrt{\text{Sampling Time}}} \tag{4-13}$$

$$X(f) = \frac{\text{fft}(w)}{N\times\text{Sampling Time}} \tag{4-14}$$

The vector of the white noises that are generated at random in the time domain is denoted as $w(t)$) and the vector that is transformed into the frequency domain is $X(f)$. The linked turbulent wind speeds' N ×1 Fourier transform vector, $V(f)$, is;

$$V(f) = H(f) \times X(f) \tag{4-15}$$

Lastly, the inverse Fourier transform of $V(f)$is used to calculate the turbulent wind speed time series:

$$V_{\text{point}}(t) = (N \times \text{Sampling Time}) \times \text{ifft}\big(V(f)\big) \tag{4-16}$$

It is necessary for $V_{\text{point}}(t)$ to be real because H is subject to periodicity. For use in simulations, the Digsilent PowerFactory stores the produced point wind speed time series in a data structure (DIgSILENT GmbH, 2015).

4.2.2. Battery Energy Storage System

Modelling BESS in PowerFactory involves simulating the complex interactions between the storage components and the grid. A BESS comprises two primary parts: the storage unit and the rectifier/inverter (DIgSILENT GmbH, 2010). The storage unit utilises electrochemical processes to store and release energy, while the rectifier/inverter is typically based on a 'Voltage Source Converter (VSC) with Pulse Width Modulation (PWM) and manages the conversion between DC and AC voltages. These components are essential for integrating BESS into power systems for applications such as frequency and voltage stabilisation and stability (Gwabavu & Raji, 2021).

i. Challenges in battery modelling

Battery modelling in PowerFactory poses two significant challenges (Fard, 2017):

- Model complexity and accuracy: The model must balance simplicity with sufficient accuracy to represent battery behaviour effectively.
- Parameter availability: Accurate models require data on battery parameters such as internal resistance, terminal voltage, and the State of Charge (SOC), which are often difficult to obtain from manufacturers.

Common battery types, such as lead-acid, nickel-cadmium (NiCd), nickel-metal hybrid (NiMH), and lithium-ion, exhibit unique behaviours that must be accounted for in the model (Stecca et al., 2020). For instance, the lead-acid batteries adhere to Peukert's Law, which describes the relationship between discharge rate and available capacity (Zhang et al., 2018):

$$C_p = I^k t \tag{4-17}$$

Where:

- Cp : Capacity (Ah),
- I: Discharge current (A),
- k: Peukert constant
- t: Discharge time (hours).

This law demonstrates that the available capacity decreases as the discharge rate increases. However, it assumes infinite capacity at zero discharge current, a limitation that must be considered in the modelling (Zhang et al., 2018). Figure 4.3 depicts a typical battery state of charge concerning internal resistance and discharge voltage.

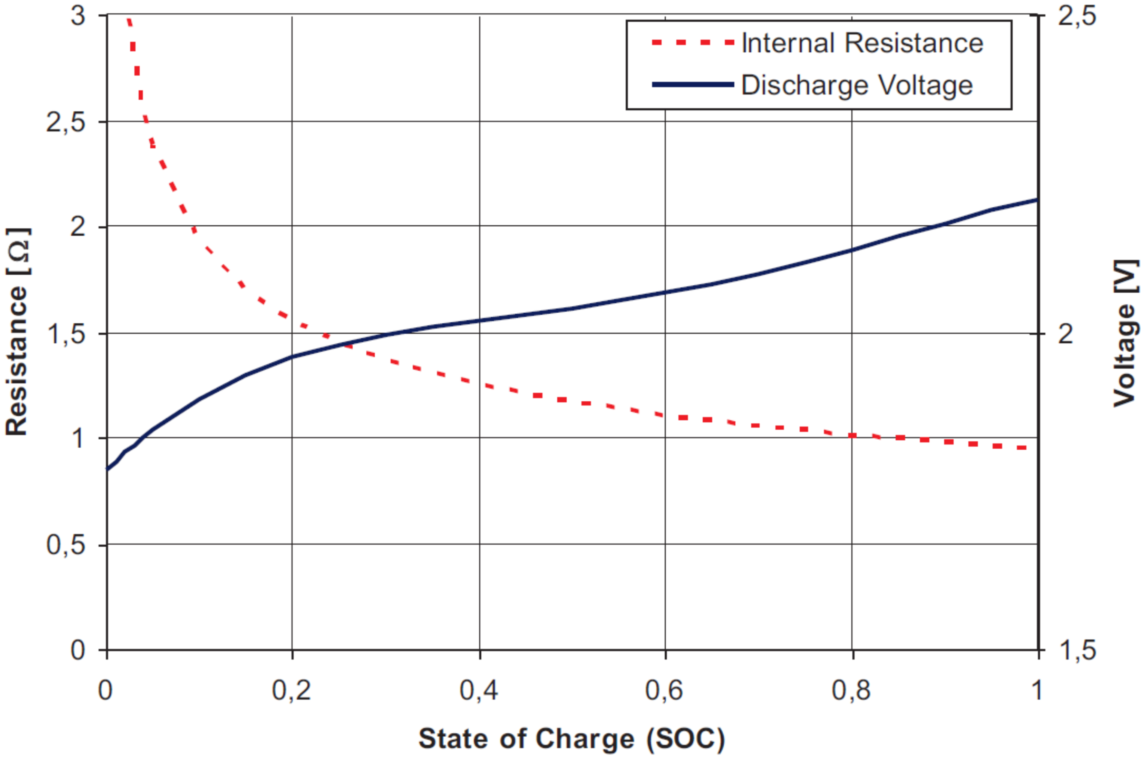


Figure 4.3: Typical discharge of the battery (DIgSILENT GmbH, 2010)

ii. Simplified battery models

For practical applications in PowerFactory, simplified models are often sufficient. These models typically assume (Liu et al., 2024):

1. Linear SOC-voltage dependency: Voltage is considered as being linearly dependent on the SOC, particularly when discharge is limited to above 20%.
2. Constant internal resistance: Assumes the resistance is small and consistent, appropriate for high-current applications.
3. Predefined capacity: Capacity is treated as constant if the discharge rate is predetermined.

The terminal voltage (U_{DC}) of a simplified model can be expressed as (DIgSILENT GmbH, 2010):

$$U_{\mathrm{DC}} = U_{\max} \cdot SOC + U_{\min} \cdot (1 - SOC) - I \cdot Z_i \qquad (4\text{-}18)$$

Where;

- $U_{\max}$, $U_{\min}$: Maximum and minimum cell voltages, respectively,
- SOC: State of Charge (SOC =1 when fully charged; SOC =0 when empty),
- I: Discharge current,
- Z_i: Internal resistance.

SOC is calculated dynamically through an integrator that tracks charge and discharge currents over time (DIgSILENT GmbH, 2010):

$$SOC = SOC_0 + \frac{1}{C}\int I \, dt \qquad (4\text{-}19)$$

Here:

- SOC_0: Initial state of charge,
- C: Battery capacity,
- I: Current over time.

iii. Advanced Battery Models

Advanced battery models incorporate nonlinear dependencies on variables such as temperature, ageing, and SOC for detailed studies. These models allow for more precise internal resistance and terminal voltage representation (Hu et al., 2019). For example:

- Nonlinear voltage-SOC relationship: Terminal voltage shows rapid changes for SOC<0.2, requiring more complex modelling.
- SOC-dependent internal resistance: Internal resistance increases significantly at low SOC values, impacting performance.

PowerFactory enables these advanced models using its Dynamic Simulation Language (DSL). With sufficient manufacturer data, the DSL-based models can accurately simulate specific battery technologies (Hu et al., 2019).

iv. Implementation in PowerFactory

In PowerFactory, a BESS can be modelled as a DC voltage source within the single-line diagram. The battery model determines the voltage output, which may use a simplified equivalent or a detailed DSL-based representation. The SOC integrator dynamically calculates the charge/discharge state while the output voltage is fed into the DC busbar for load flow analysis. The simplified model assumptions allow for efficient simulation in cases where detailed behaviour is unnecessary. For instance, the model can approximate performance for predefined discharge rates by assuming constant capacity and internal resistance. However, more complex models are recommended for applications with varying discharge conditions or critical performance requirements. BESS modelling in PowerFactory offers the flexibility to use simplified or advanced approaches, depending on the application. Simplified models provide a quick and functional representation, while advanced DSL-based models are necessary for detailed analyses. By accurately representing SOC, internal resistance, and terminal voltage, PowerFactory enables the effective integration of BESS into the power systems for enhanced stability and reliability (DIgSILENT GmbH, 2010).

4.2.3. The Development Model for Wind Farm BESS

The development of the model for integrating BESS with wind farms is designed to ensure the delivery of dispatchable power by compensating for the power mismatches caused by the variability of wind power. The variability and unpredictability of wind energy facilitate reliable power supply over specified durations, usually one hour, to satisfy power market demands and enhance grid stability (Khalid et al., 2018). Wind power systems predict and report average power outputs for specified intervals; however, discrepancies frequently arise due to variations in wind speed and forecasting inaccuracies, thereby leading to power mismatches and possible market penalties (Bokde et al., 2018). BESS rectifies these discrepancies by accumulating surplus energy during abundant wind power and releasing energy during deficits, guaranteeing the reliable delivery of scheduled power (Ullah et al., 2024). The scheduled power is determined by a sliding average of projected wind power across one-hour intervals, mitigating fluctuations and improving stability. Incorporating BESS enables wind farms to enhance market compatibility and operational RE (de Siqueira & Peng, 2021).

Figure 4.4 shows a portion of a scholarly article that describes a wind farm model that includes a Battery Energy Storage System (BESS) and planned power calculations. Model of Wind Farm BESS: The integration of a wind turbine (P_w), a battery charger, an inverter, and the power output (P_out) connected to a grid via transmission lines is depicted in Figure 4.4, which represents the Wind-farm BESS model (Gholami et al., 2021). In order to ensure dependable power delivery, the BESS is integrated to address differences between expected and actual power outputs. It does this by storing excess energy and releasing it during deficiencies. Calculation of Scheduled Power: A sliding average of predicted wind power over specified time periods is used to calculate the scheduled power, P_s(t).

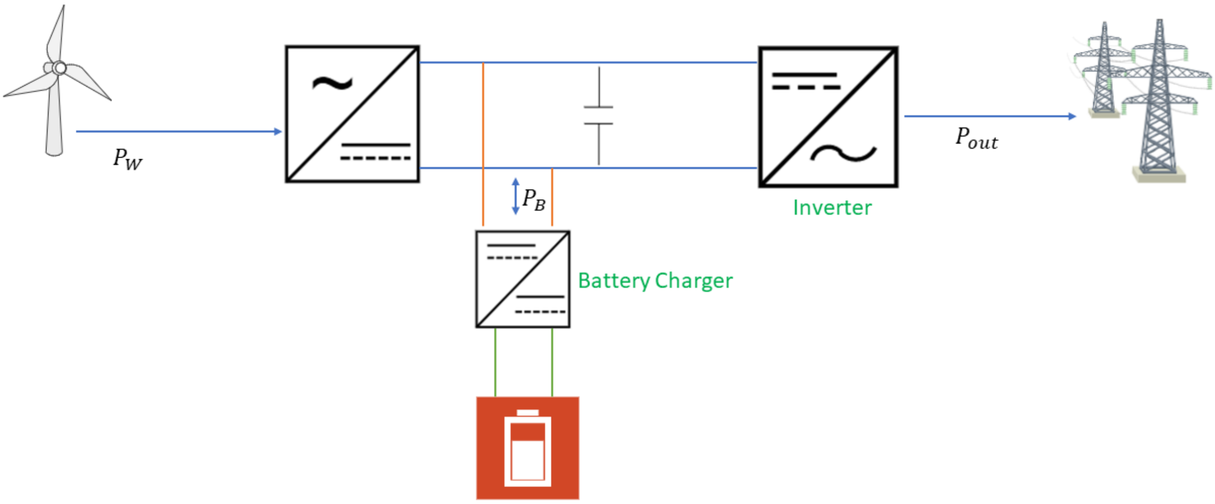


Figure 4.4: Wind farm BESS model (Gholami et al., 2021)

The scheduled power is calculated using the sliding average of forecasted wind power over one-hour intervals (Gholami et al., 2021):

$$P_S(t_i) = \frac{1}{\Delta t}\int_{t_i-T/2}^{t_i+T/2} P_f^W(t)\, dt, \quad P_S(t) = P_S(t_i)\, \forall\, t_i - T/2 < t < t_i + T/2 \tag{4-20}$$

where $P_S(t_i)$ and $P_f^W(t)$ represent the scheduled power and the forecasted wind power, respectively, and T is the commitment interval (one hour in this model). The power mismatch is defined as the difference between the actual wind power $P_W(t)$ and the scheduled power $P_S(t)$

$$P_m(t) = P_W(t) - P_S(t) \tag{4-21}$$

To achieve dispatchable wind power and maintain constant power delivery over the defined intervals, the BESS compensates for this mismatch by delivering or storing the mismatch power:

$$P_B(t) = P_m(t) \tag{4-22}$$

The energy profile and the battery's state of charge are determined by integrating the power profile over time:

$$E_B(t) = E_B(0) + \int_0^t \frac{1}{2}\left[\eta_C \left(1 + \text{sign}\left(P_B(t)\right)\right) + \eta_D \left(1 - \text{sign}\left(P_B(t)\right)\right)\right] P_B(t)\, dt \tag{4-23}$$

$$SOC(t) = \frac{E_B(t)}{E_r} \tag{4-24}$$

Here, η_C and η_D are the charge and discharge efficienciesE_B is the rated capacity of the battery, and $E_B(t)$ is the energy profile of the battery.

The required energy capacity E_r^B for the BESS is determined based on the maximum energy level in the long-term profile:

$$E_r^B = \max(\text{Long-term energy profile}) \tag{4-25}$$

This model provides a systematic approach to integrating BESS with wind farms, ensuring reliable, dispatchable power delivery by smoothing out fluctuations and compensating for mismatches in wind power. The model establishes a foundation for efficient energy storage and power management in wind farm systems by defining scheduled power, addressing mismatch power, and calculating energy profiles and capacities. To enhance the coordination and functionality of the system, a wind farm controller is implemented to synchronise turbine operations using DIgSILENT PowerFactory scripts for executing multi-rate control loops. This extensive modelling and simulation framework provides an efficient and precise foundation for developing and optimising wind farms and BESS integration (Gholami et al., 2021).

4.3. Controller design

Integrating BESS with wind farms enhances power management through battery storage to stabilise grid operations and dynamic regulation of wind turbine power set-points (Liu et al., 2020; Zou et al., 2015). A power converter, a Rotor Side Converter (RSC) and a Grid Side Converter (GSC)control the power exchange within the grid, a gearbox connects the DFIG to the blades to capture air kinetic energy, and a BESS is connected to the DC in a typical wind energy conversion system as shown in Figure 4.5. The two mass mechanical models are compatible with the dynamic depiction of the wind system's mechanical components in this work (Gomez et al., 2020).

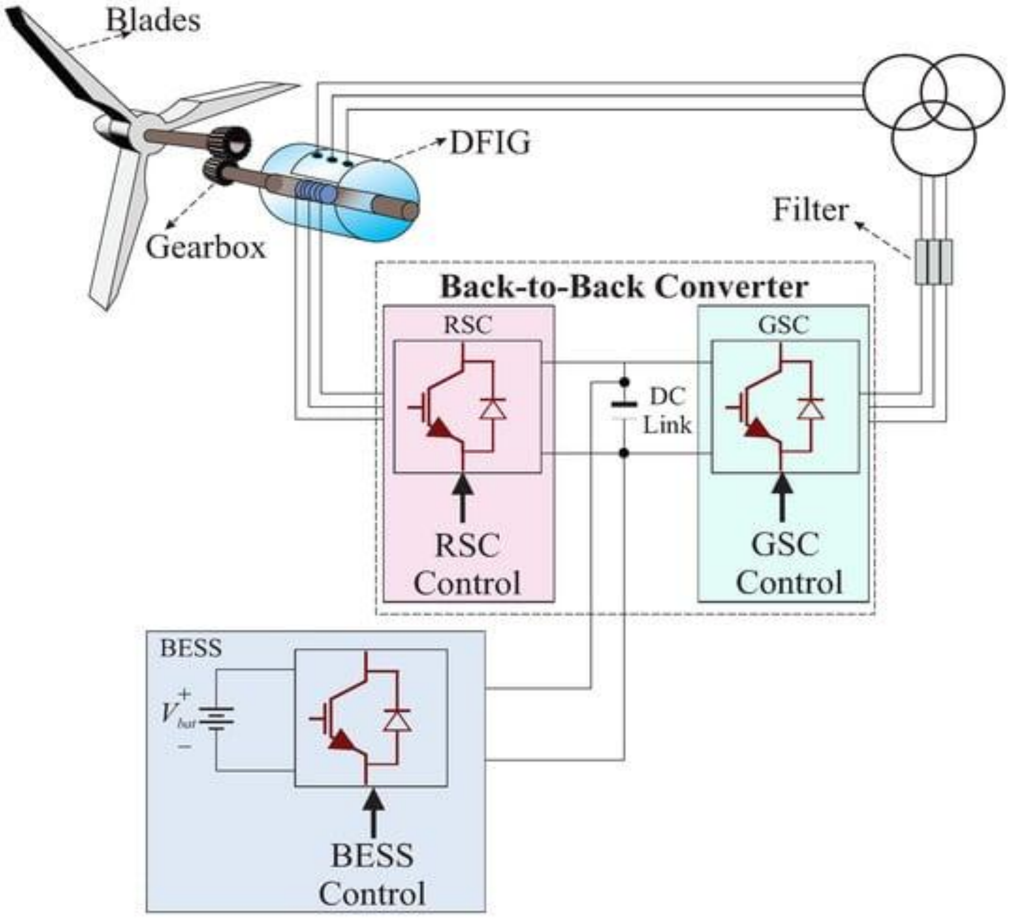


Figure 4.5: **Wind farm BESS controls (Gomez et al., 2020)**

A three-phase, two-level converter matches the RSC and GSC. The converter has six IGBTs with antiparallel free-wheeling diodes. The control algorithm is engineered to guarantee dependable power distribution, offer frequency and voltage assistance, and enhance grid stability. The system uses battery charge management, droop control, synthetic inertia response, primary frequency response, and power reference tracking to accomplish various operational objectives (Gomez et al., 2020).

4.3.1. Control Objectives and Structure

The wind farm controller's primary objective is power reference tracking, which ensures that the grid has the electricity it needs (Gwabavu & Raji, 2021). The primary frequency control routine concurrently monitors grid frequency deviations and activates responses upon exceeding thresholds (Attya et al., 2018; Ullah et al., 2024). Figure 4.6 shows the control scheme for the frequency of active power control.

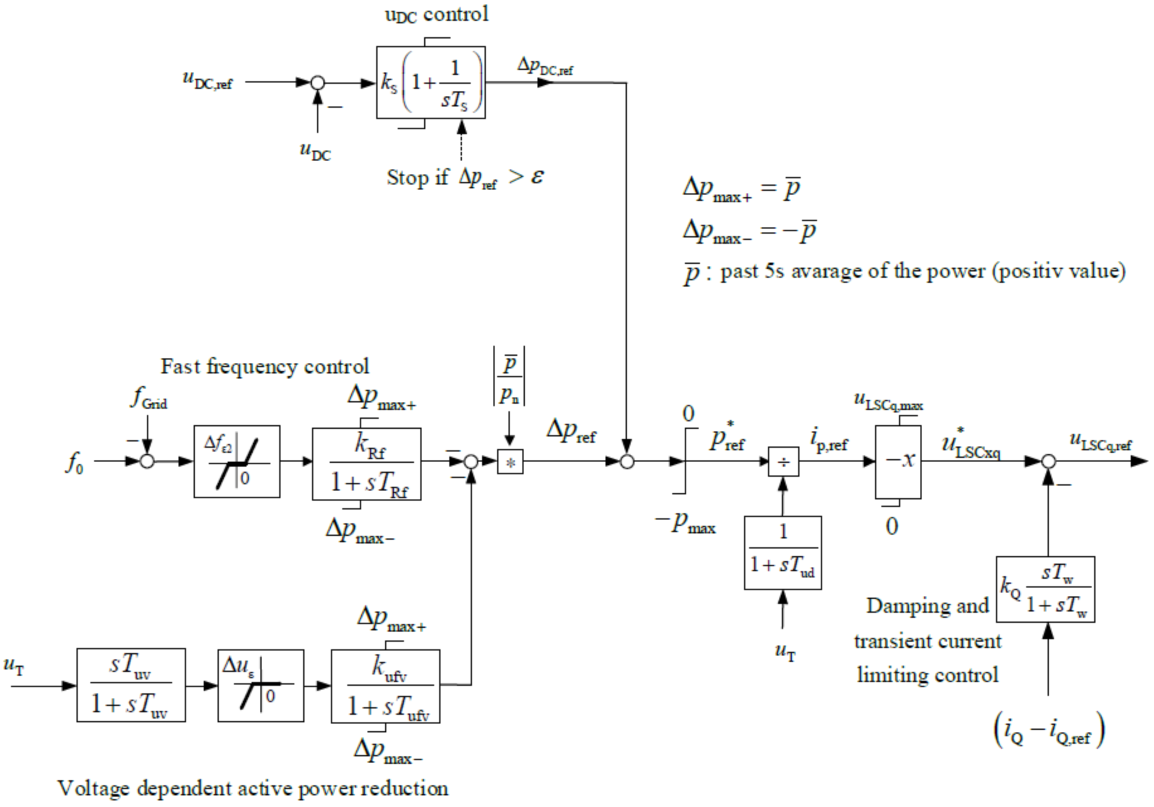


Figure 4.6: **Control scheme for frequency and power control (Korai & Erlich, 2015)**

Incorporating BESS enables the system to efficiently manage power discrepancies by storing excess energy or discharging to address deficits. The algorithm utilises plant automation controller supervisory flags to ascertain the operational status of each wind turbine and its ability to facilitate power adjustments. These flags classify turbines into operational zones according to traffic light and black limit regulations, ensuring safe functionality while preserving adaptability (Erlich et al., 2017).

4.3.2. Power Set-Point Dispatch

The wind farm controller allocates power set-points (Δpi) to turbines according to the wind farm's reference power (ΔP) and the operational status of the turbines. BESS enhances this dispatch by regulating power discrepancies, where $P_m(t)$ denotes the discrepancy in power between actual and scheduled values. The power set-point dispatch unit allocates the necessary farm power adjustment ΔP_{dem} among turbines based on their operational status (Poushpas & Leithead, 2015).

$$\Delta p_i = -\Delta P_{\text{dem}} \frac{P_{\text{traffic-light},i}}{P_{\text{total}}} \tag{4-26}$$

Where, $P_{\text{traffic-light},i}$ denotes the adjustment power designated for turbine i within its operational domain under traffic light conditions, P_{total} represents the aggregate of $P_{\text{traffic-light},i}$ across all turbines and ΔP_{dem} signifies the requisite power adjustment level for the wind farm (e.g., curtailment level) (Poushpas, 2016).

4.3.3. Frequency and Voltage Control

Frequency and voltage control are crucial in maintaining grid stability and ensuring reliable energy delivery (Jarosz, 2024).

i. Frequency regulation

Frequency regulation is essential for sustaining grid stability in the integrated wind farm and BESS. The system observes discrepancies between the reference frequency (f_{ref}) and the actual grid frequency (f_{grid}) (Poushpas, 2016):

$$\Delta f = f_{\text{ref}} - f_{\text{grid}} \tag{4-27}$$

When the grid frequency fluctuates:

- Negative frequency deviations ($\Delta f < 0$) signify an excess of energy supply. The BESS charges by absorbing surplus power from the grid, alleviating the frequency rise.
- Positive frequency deviations ($\Delta f > 0$) signify an energy deficit. The BESS releases stored energy to address the shortfall, stabilising the frequency.

The system uses frequency droop control to establish the correlation between frequency deviation and battery power activation. The droop function regulates the complete activation of BESS power by the extent of frequency deviation.

$$P_{\text{BESS}} = \frac{\Delta f}{\text{droop}(R)} \tag{4-28}$$

This ensures a proportional response from the BESS, aligning with grid stability requirements.

ii. Voltage Control

Voltage regulation in the wind farm BESS stabilises grid voltage by managing reactive power (Q) (Hemmati et al., 2018). The system quantifies the voltage deviation (Δv) as the disparity between the reference voltage (V_{ref}) and the actual grid bus voltage (V_{ref}) po(Ullah et al., 2024; Poushpas, 2016):

$\Delta v = V_{\text{ref}} - V_{\text{ref}}$ (4-29)

Contingent upon the orientation of voltage deviation:

- Positive voltage deviations (Δv > 0) signify inadequate reactive power in the grid. The BESS supplies reactive power to elevate the grid voltage.
- Negative voltage deviations (Δv < 0) signify an excess of reactive power in the grid. The BESS absorbs reactive power to reduce voltage levels.

The system employs voltage droop control to create a proportional correlation between voltage deviation and reactive power response.

$$Q_{\text{BESS}} = \frac{\Delta v}{\text{droop}(R)} \tag{4-30}$$

This ensures efficient reactive power regulation, enhancing voltage stability while complying with grid codes. By dynamically managing both frequency and voltage deviations, the integrated control of BESS and wind turbines enables robust support for grid operations, ensuring reliability and stability in renewable energy systems (Gwabavu & Raji, 2021).

4.3.4. Synthetic Inertia and Droop Control

An effective solution for stabilising the power grid is leveraging advanced control strategies such as synthetic inertia response and droop control. These mechanisms ensure grid stability by addressing frequency deviations caused by fluctuations in power supply and demand (Shobug et al., 2024; Loza et al., 2024).

i. Synthetic inertia response

Synthetic inertia response addresses rapidly changing grid frequencies, measured as ROCOF $\frac{df}{dt}$ (Eriksson et al., 2018). Synthetic inertia uses BESS and other rapid energy storage technologies to simulate the spinning mass of conventional generators. The synthetic inertia response power adjustment is directly proportional to ROCOF (Makolo et al., 2024):

$$\Delta P_{\text{synthetic}} = K \cdot \frac{df}{dt} \tag{4-31}$$

Here:

$\Delta P_{\text{synthetic}} =$: Synthetic inertia power adjustment,

K: Gain constant representing BESS equivalent inertia.

The swing equation, which models the grid's mechanical and electrical power dynamics, is used to calculate power adjustments:

$$J\omega_{\text{grid}}(t)\frac{d\omega_{\text{grid}}}{dt} = P_{\text{mec}}(t) - P_{\text{elc}}(t) \quad (4\text{-}32)$$

Where:

- J: Moment of inertia of the system,
- $\omega_{\text{grid}}(t)$: Grid angular frequency,
- $P_{\text{mec}}(t)$: Mechanical power input,
- $P_{\text{elc}}(t)$: Electrical power output.

Synthetic inertia allows the BESS to instantly deliver or absorb power in response to ROCOF, stabilising the grid and reducing frequency deviations. This functionality is crucial during high-magnitude disturbances like generation losses or load surges (Makolo et al., 2024).

ii. Droop control

Droop control supports synthetic inertia by managing slower frequency deviations and spinning reserves for the primary frequency response (Chen et al., 2024). The power output (ΔP_{droop}) is adjusted by the droop control mechanism based on the frequency deviation (Δf) (Lamaouche et al., 2022):

$$\Delta P_{\text{droop}} = m \cdot \Delta f \quad (4\text{-}33)$$

Where:

- ΔP_{droop}: Power adjustment for droop control,
- m: Droop slope, which defines the sensitivity of the response

The power adjustments increase proportionally with frequency deviations in droop control. This method gradually corrects frequency deviations while maintaining spinning reserves for unexpected events. To maintain proportionality and effectiveness under different operating conditions, the droop slope (m) is dynamically adjusted based on system power (Chen et al., 2024; Lamaouche et al., 2022).

4.3.5. Battery Management and Charge Control

The BESS controller regulates the SOC by keeping it within specified parameters to enhance performance and prolong battery lifespan (Ratshitanga et al., 2024). The detailed control methodology of BESS is illustrated in Figure 4.7.

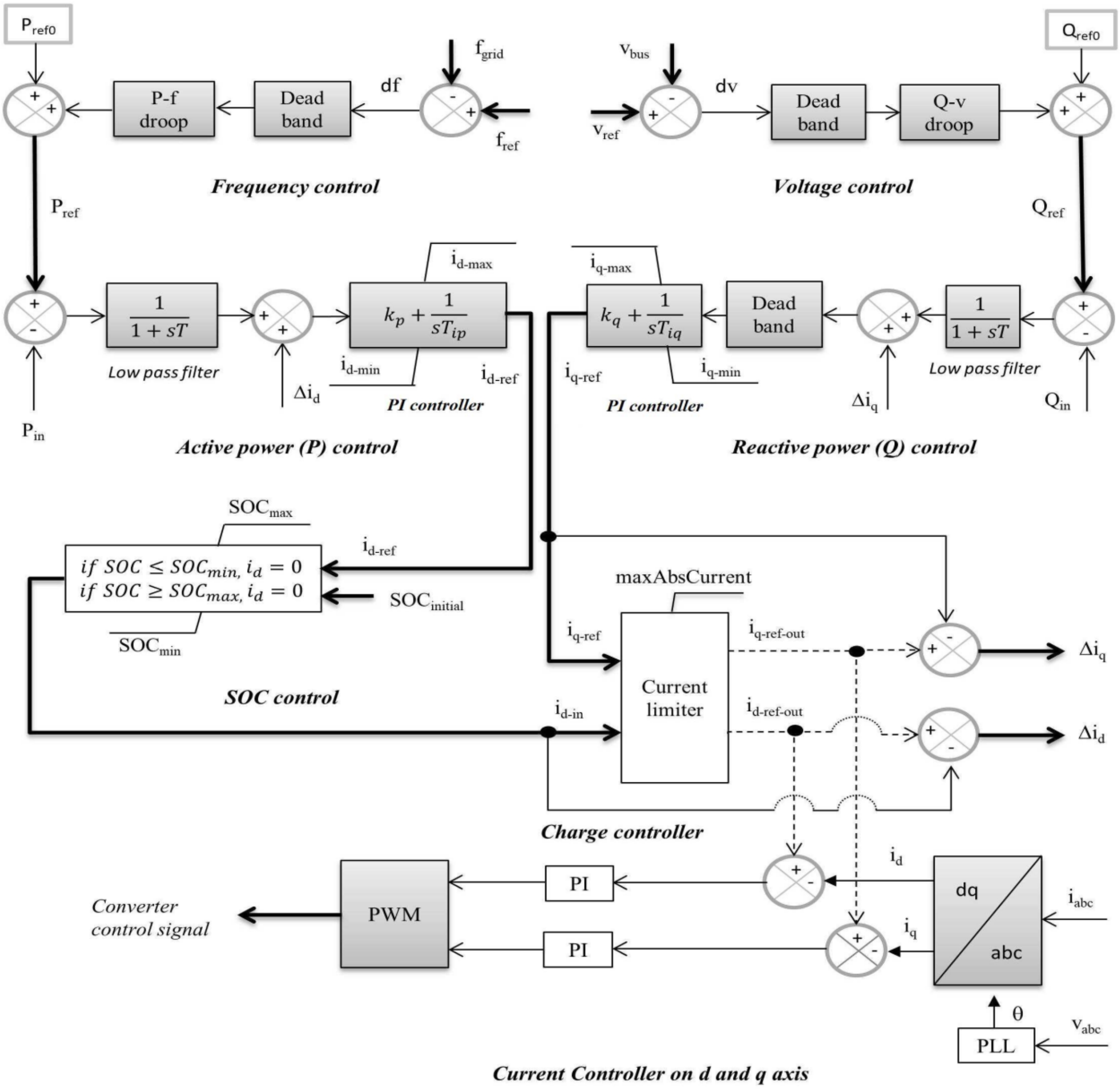


Figure 4.7: BESS control techniques (Datta et al., 2019)

The SOC indicates the battery's current energy level in relation to its capacity and is continuously modified by tracking power input and output over time. The battery functions solely within a defined SOC range, charging under surplus conditions and discharging during deficits, thus averting overcharging or excessive discharging. The charge/discharge control meticulously manages the power flow to and from the grid, ensuring safety, reliability, and adherence to the state of charge constraints. It adjusts dynamically according to grid conditions, allowing the BESS to respond effectively to energy demand or supply variations. This functionality and its fundamental architecture, consisting of a battery bank, a bidirectional DC/AC converter, and a grid-connected transformer, facilitate seamless integration with the grid. BESS is essential for ensuring grid reliability and stability, augmented by frequency regulation, voltage stabilisation, active/reactive power management, and accurate current control along the Direct (d) and Quadrature (q) axes (Ratshitanga et al., 2024; Datta et al., 2019).

4.4. Testing of the System Model

4.4.1. Case Study

The Chaba Wind Farm BESS network features a total power capacity of 21 MW, supported by seven wind turbines, each with a power output of 22 kV and a capacity of 3.075 MW. Figure 4.8 provides a detailed illustration of the network layout, showcasing the integration of wind turbines with the lithium battery system to create a sustainable and efficient energy solution.

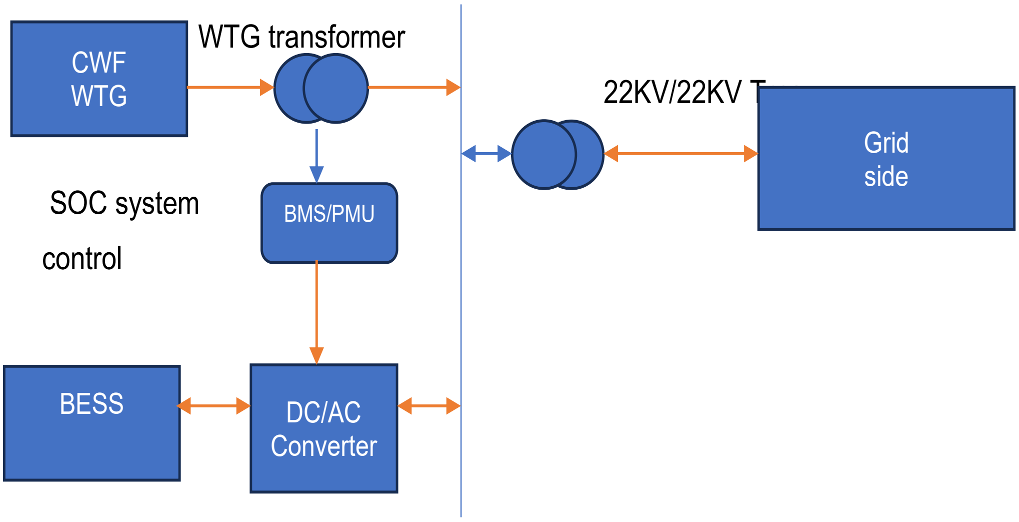


Figure 4.8: Chaba Wind Farm BESS structure Chart

A single 1:1 transformer is employed within the network, operating with an input and output of 22 kV without any step-up or step-down mechanism. The BESS system integrates lithium battery technology to enhance energy efficiency and storage capabilities. The lithium BESS comprises of multiple modular units designed to provide a total storage capacity of 7 MWh, sufficient for seven hours of continuous operation. Each module is engineered to optimise energy storage and discharge efficiency, addressing the inherent challenges of intermittent energy generation in renewable energy systems. The grid supply operates at 22 kV and is connected to the wind turbines through a streamlined distribution network to minimise energy losses. The Chaba Wind Farm, chosen for its standard operational features and strategic location, demonstrates the potential of integrating advanced energy storage systems with renewable energy generation. The study focused on the wind farm's functional elements, its lithium BESS's scalability, and the technical parameters contributing to its operational success.

Figure 4.9 shows the annual production of four wind farms, including Chaba energy production.

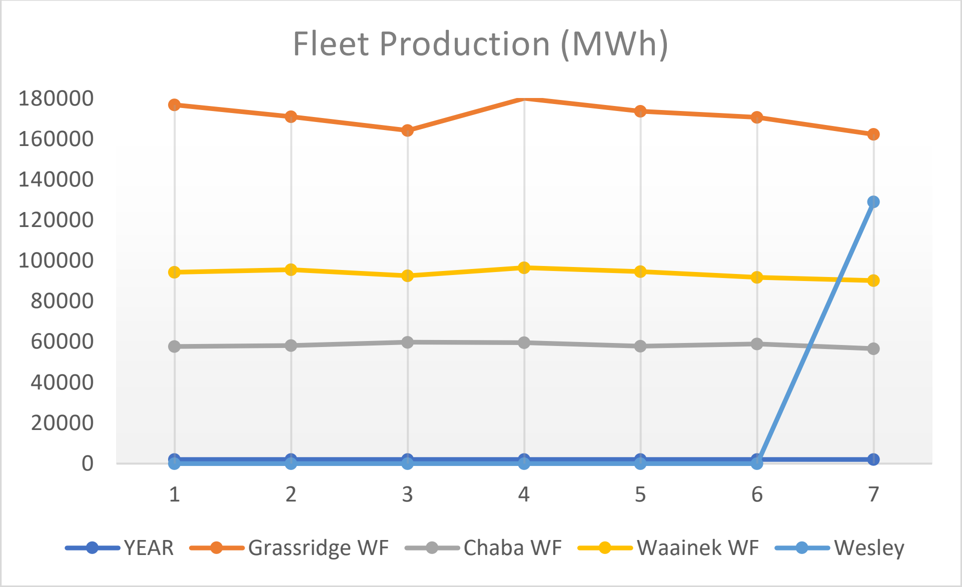


Figure 4.9: Wind farms energy production

Table 4.1: Wind farms energy production

Actual Production				
YEAR	**Grassridge WF**	**Chaba WF**	**Waainek WF**	**Wesley**
2016	177,006.308	57,755.364	94,426.994	0.000
2017	171,057.888	58,298.190	95,641.611	0.050
2018	164,323.676	59,884.137	92,581.042	0.000
2019	180,161.435	59,670.604	96,628.319	0.000
2020	173,732.970	57,886.237	94,654.991	0.000
2021	170,712.654	59,013.642	91,929.515	0.000
2022	162,373.828	56,700.893	90,259.972	129,046.387
total	**1199368.76**	**409209.07**	**656122.44**	**129,046.387**

Figure 4.10 below represents a spread of the annual wind speed for the Chaba Wind Farm of wind speed against power produced. The relationship between available wind speed and expected power produced is known from the mathematical algorithm of the turbine operations. With that being said, the BESS integration to overcome the low producing times is introduced and configured to mitigate intermittency and the variability of wind power, as well as to optimise energy storage and dispatch, and provide grid services.

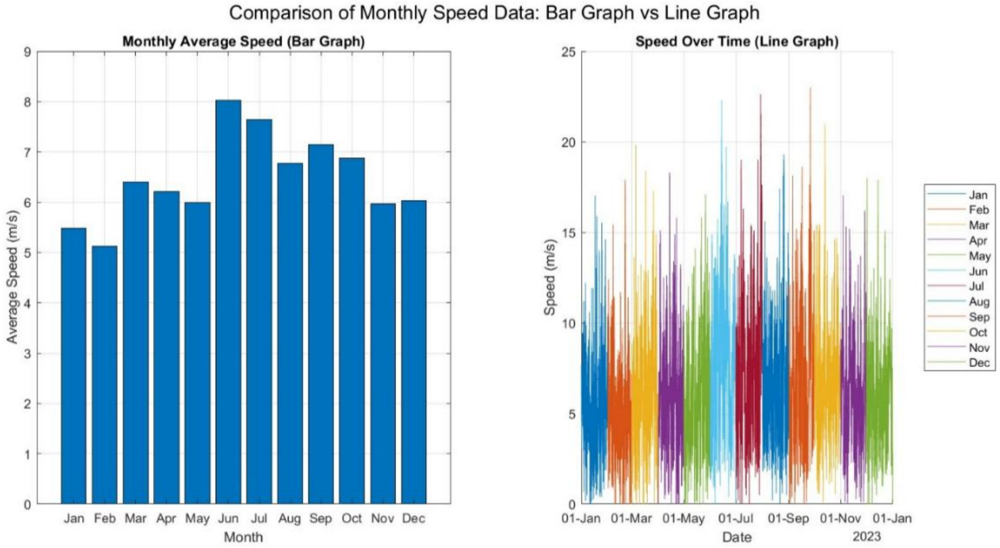


Figure 4.10: **Wind speed Simulation Method**

The simulation evaluated the technical integration and operational efficiency of the Chaba Wind Farm and its Battery Energy Storage System (BESS) under varying grid conditions. These tests are designed to validate the robustness of the Voltage-Source-Controlled Converter (VSCC) solution and analyse system performance during both normal operations and fault scenarios. The selected test cases address real-world challenges, ensuring the system's ability to maintain stability, resilience, and efficiency in practical applications.

The process involved the following key steps:

Case 1: Initial operation – Establishing baseline performance

- The system operates under normal load conditions to establish baseline performance metrics, ensuring a reference point for subsequent tests.
- This phase validates the synchronisation of wind turbines and BESS with the grid, confirming that the system functions as expected under normal conditions.
- Rationale: Ensuring proper grid synchronisation is crucial for maintaining system efficiency and power quality in renewable energy integration.

Case 2: Three-phase fault – Evaluating system resilience

- Three-phase fault was introduced for 150 ms to assess the system's ability to withstand and recover from severe disturbances.
- Both Electromagnetic Transient (EMT) and Root Mean Square (RMS) simulations are conducted to provide a detailed analysis of transient and steady-state behavior.
- Rationale: Grid disturbances, such as faults, can cause significant voltage and frequency instability. Wind farms and BESS must demonstrate fault ride-through capability to comply with grid code requirements and ensure a continued power supply.

Case 3: Load trip – Assessing stability under sudden demand reduction

- A 15 MW load disconnection was simulated to observe how the system reacts to sudden decreases in demand and whether the BESS can mitigate potential power imbalances.
- The response of the BESS in adjusting power output to maintain grid stability was analysed.
- Rationale: Load shedding events and sudden consumer disconnections are common in grid operations. Testing the system's ability to manage reduced demand ensures effective frequency regulation and stability.
- **Case 4: Load connection – Evaluating response to sudden demand increase**
- A 15 MW load was added to the system to analyse how the wind farm and BESS respond to rapid demand surges.
- The test assessed the system's voltage stability and power quality maintenance during increased load conditions.
- Rationale: Grid-connected renewable energy systems must be capable of handling unexpected demand fluctuations. Ensuring a smooth transition during load additions minimises voltage sags and prevents system-wide instability.

4.4.2. Simulation Time Frames and Analytical Approach

The simulations were conducted across multiple time frames to capture various operational dynamics:

- 2.5 seconds – Captures fast transient events and immediate system responses.
- Up to 50 seconds – Observes long-term transient behaviour and system stabilisation post-disturbance.
- 30 minutes – Assesses steady-state operations, energy management efficiency, and prolonged grid stability.

4.4.3. Expected Outcomes and Significance

This structured simulation approach provided comprehensive insights into the operational dynamics of the Chaba Wind Farm with its lithium BESS. The outcomes:

- Demonstrated system resilience and fault recovery capabilities, ensuring compliance with grid stability requirements.
- Validated the efficiency of BESS integration in balancing power supply during demand variations and disturbances.
- Established the wind farm's potential as a scalable model for future renewable energy projects, contributing to a more stable and sustainable energy grid.

By systematically analysing these scenarios, the study determined the feasibility and reliability of hybrid renewable energy solutions in supporting grid stability, operational efficiency, and sustainable energy transition efforts.

Case 1: Initial Operation

i. Wind farm

Figure 4.11 shows that the voltage magnitude at the wind farm bus stabilizes at one per unit (1 p.u.), and simultaneously, Figure 4.12 demonstrates that the system's frequency stays the same at 50 Hz. These observations provide evidence that the network system within the DigSilent simulation environment is reliable and operates appropriately.

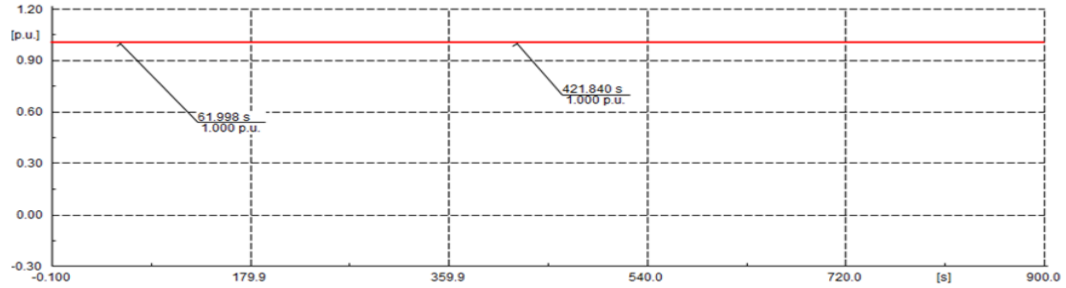


Figure 4.11: **Wind farm magnitude voltage**

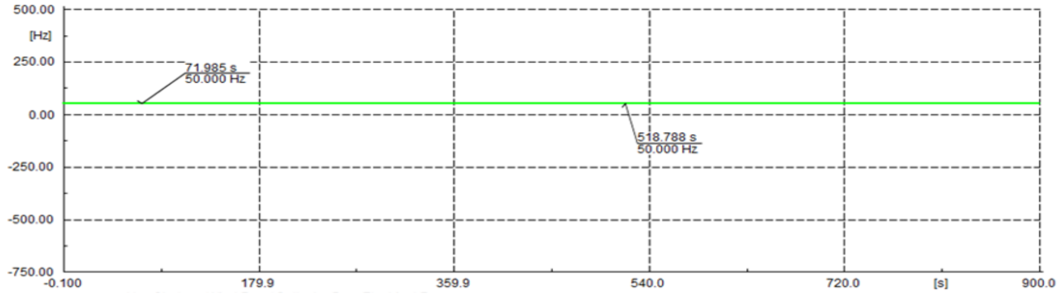


Figure 4.12: **Wind farm frequency magnitude**

ii. Battery Energy Storage System (BESS)

Figure 4.13 provides a comprehensive display of the BESS parameters prior to integration, showcasing Ucell in per unit (pu) and SOC.

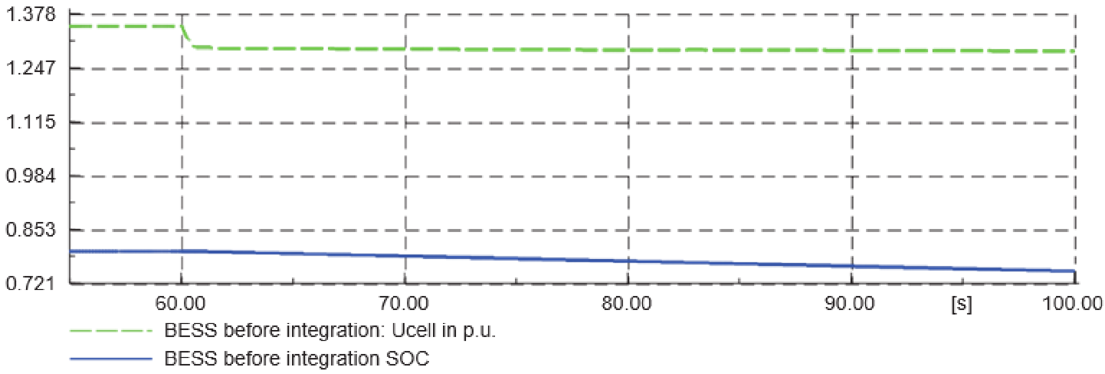


Figure 4.13: **BESS before integration**

It is noticeable that the battery's behaviour remains uniform for over 100 seconds. This pattern of consistency indicates that the battery is usually charged battery. States of charge show oscillations after wind farm integration, as shown in Figure 4.14.

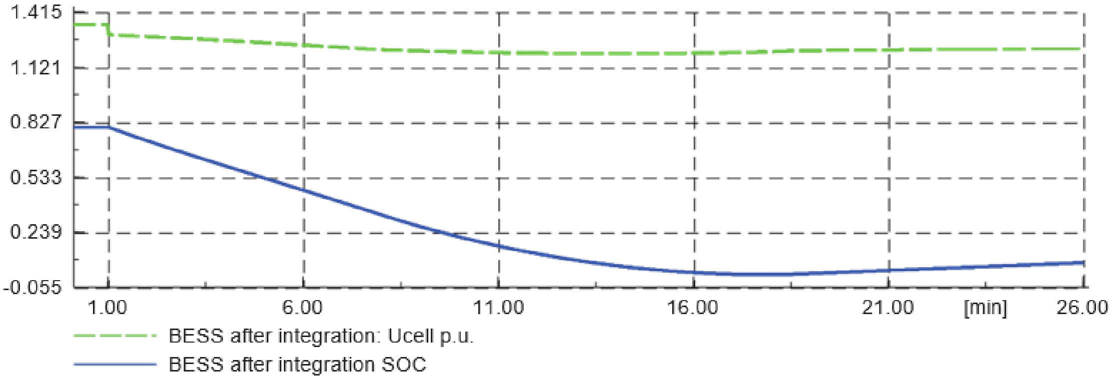


Figure 4.14: **BESS after integration**

It is possible to observe these variations as they develop throughout time. The number of times the battery is charged and discharged, its total capacity, the amount of current being injected into or removed from it, and its efficiency contribute to its fluctuating state of charge.

iii. Grid

Figure 4.15 illustrates the magnitude of the voltage remaining constant over time at one per unit (p.u).

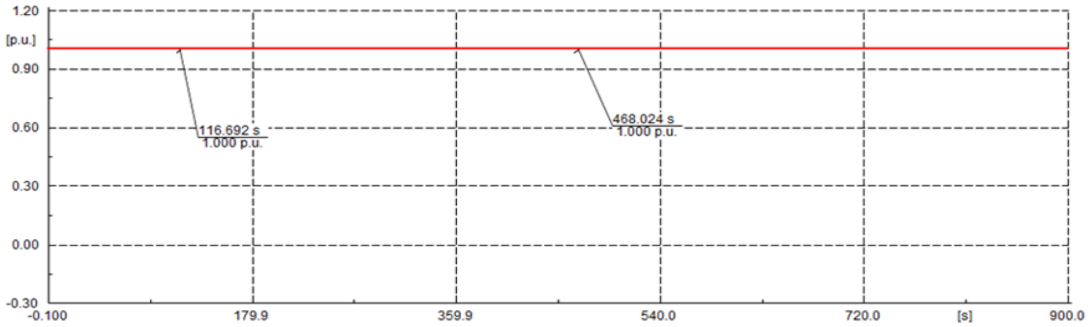


Figure 4.15: **Grid bus voltage**

Figure 4.16 depicts the frequency of the grid bus remaining constant across the temporal axis at 50 Hz. Therefore, the wind farm BESS system can be integrated with the grid without challenges.

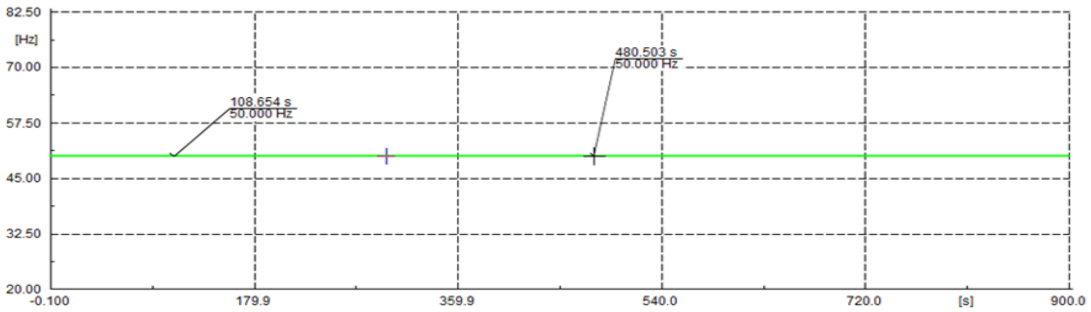


Figure 4.16: Grid bus frequency

iv. Wind Farm BESS connected to the grid

Predicting wind power generation, load demands, and other variables can optimize BESS charging and discharging to maximize system performance of reactive power, grid voltage, wind farm speed, and wind farm power.

a. Reactive power

The reactive power of a wind farm with and without BESS is shown in Figure 4.17.

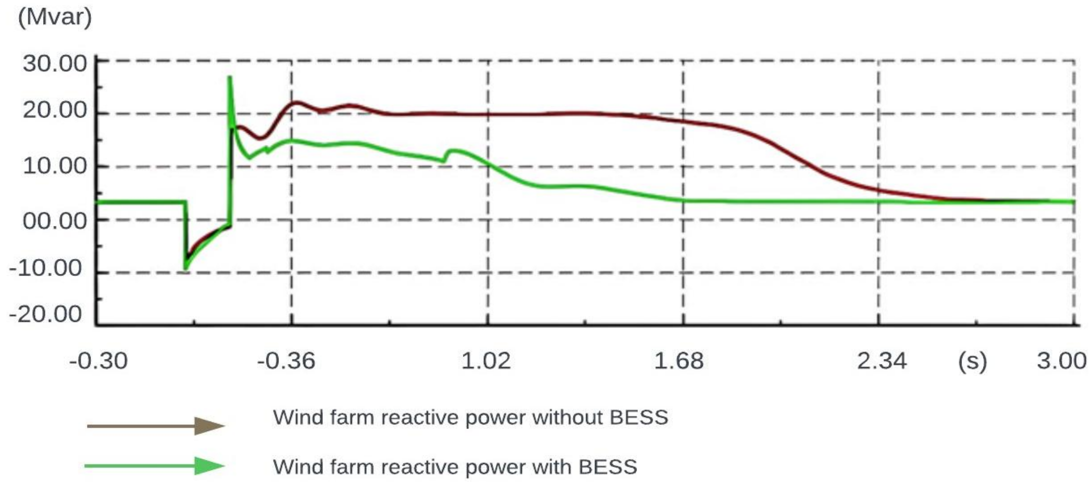


Figure 4.17: Wind farm reactive power

The wind farm will have less control over the reactive power without BESS, resulting in more significant fluctuations. This can lead to grid instability, voltage variations, and power quality issues. Furthermore, it shows how a BESS can aid in reactive power regulation when used with a wind farm. The BESS can supply or absorb reactive electricity as needed to mitigate the effects of the wind farm's sporadic power output and keep the grid stable. This leads to a reduction in reactive power fluctuations and improves the overall power quality.

b. Grid bus voltage

In Figure 4.18, Without a BESS, the wind farm's voltage control is less effective, thereby leading to higher voltage fluctuations and potential issues related to grid stability. With BESS: the BESS maintains constant bus voltage by regulating active and reactive power input and output. Therefore, the BESS can better mitigate voltage spikes and maintain grid stability.

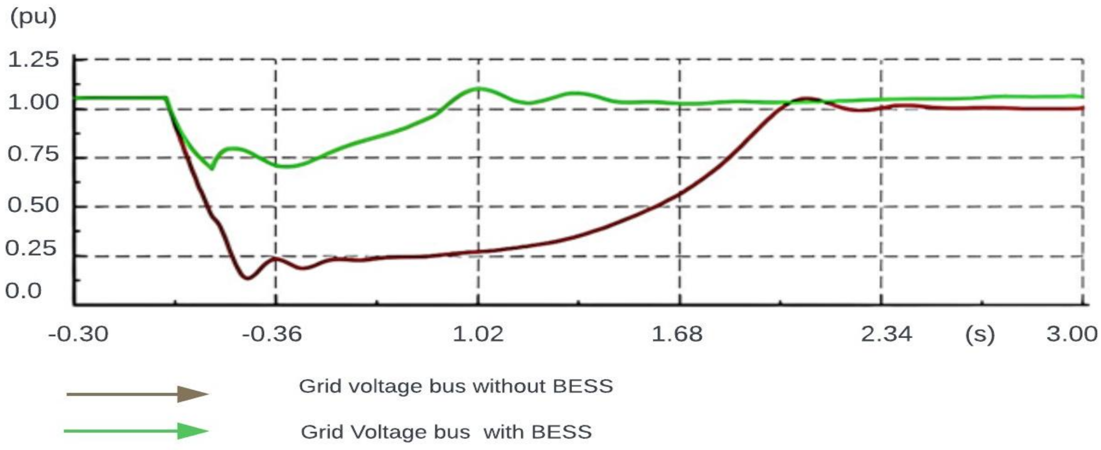


Figure 4.18: Grid voltage bus

c. Wind farm speed

Without BESS: As shown in Figure 4.19, there is more variance in the power distributed into the grid due to fluctuations in the power generated by the wind farm in response to changes in wind speed. Extra balancing capacity may be needed to keep the grid running smoothly.

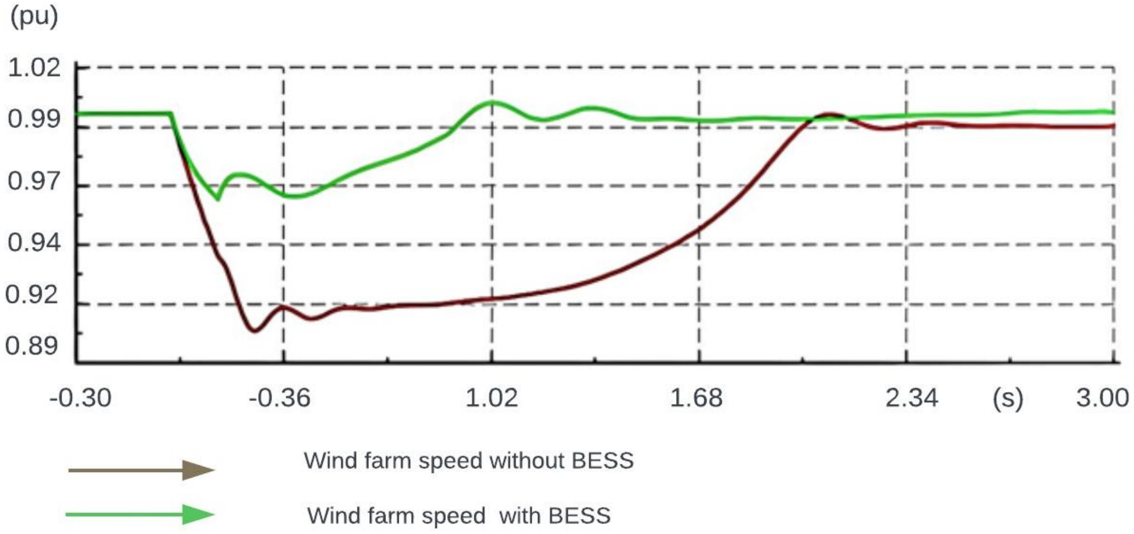


Figure 4.19: Wind farm speed

With BESS: When wind speeds are high, the BESS can store excess energy and release it when winds go down. The result is a more consistent flow of electricity from the wind farm.

d. Wind farm power

In Figure 4.20, without BESS, the active power it sends into the grid will be more erratic and less reliable. Because of this, grid support services like spinning reserves may be needed to keep the grid stable and reliable.

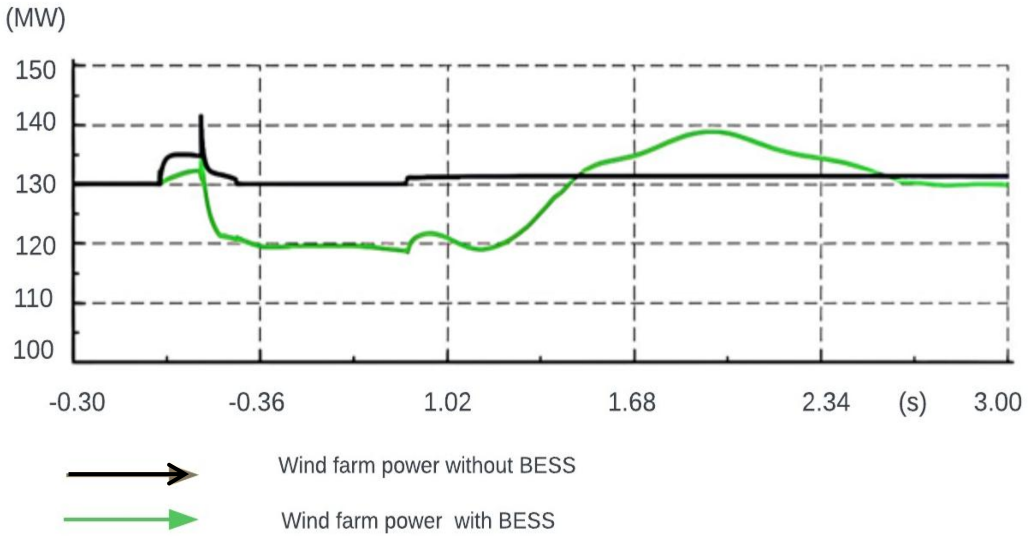


Figure 4.20:Wind farm active power

With BESS: The BESS can act as a buffer, storing the excess energy generated during high wind speeds and releasing it when the wind speeds are low or during periods of high demand. This results in a more stable and consistent active power output to the grid, thus reducing the need for additional grid support services. Also, the wind farms with BESS can quickly regulate active power output and minimise frequency deviations, resulting in more stable and reliable grid performance.

Case 2: 3 phase faults

PowerFactory provides advanced short-circuit calculations using the complete superposition method to determine operational fault currents accurately. It adheres to international standards such as IEC 60909, IEEE 141/551, and ANSI C37, ensuring precise fault current analysis at specific network operating points. The tool supports detailed fault analysis, including dynamic voltage response for generators connected via power electronics. It allows customisable fault scenarios, making it highly effective for analysing three-phase fault conditions in complex power systems (DIgSILENT, 2024). Figure 4:21 shows the wind farm BESS and grid connection of three-phase faults in Chaba Wind Farm.

i. Wind farm BESS

During a three-phase fault, one phase may momentarily be faulted before the other two, which is important in high-speed protection. At the fault, the voltages to neutral are zero. Figure 4.21 (a-d) depicts that in a wind farm without a BESS, active power output drops significantly due to voltage collapse, reactive power support is limited to the wind turbines' capabilities, frequency deviations are more pronounced due to low system inertia, and voltage recovery is slow, thereby risking prolonged instability. In contrast, with a BESS, the system becomes more resilient as the BESS can inject active power to stabilise the grid, provide reactive power to support voltage recovery and respond quickly to frequency deviations, thus ensuring faster recovery and improved stability during and after the fault.

Case 2: 3 Phase Fault Results

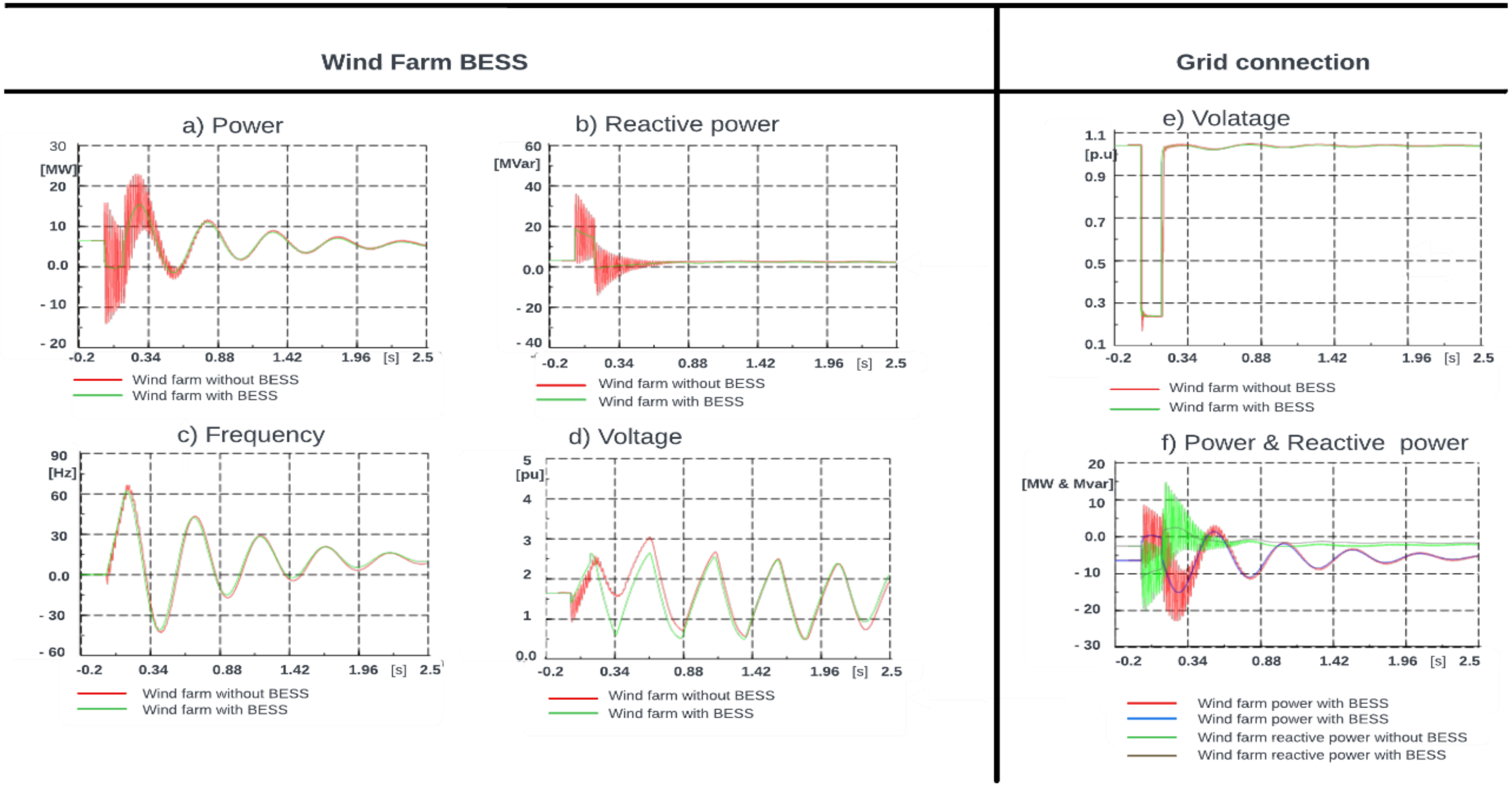


Figure 4.21: Three-phase fault

ii. Grid connection

Figure 4.21 (e) depicts that when the wind farm is connected to the grid, the behaviour of power, reactive power, and voltage during a three-phase fault varies significantly with and without a BESS. Figure 4.21 (f) shows that without a BESS, the active power output from the wind farm drops sharply due to the voltage collapse at the fault location, as there is no alternative source to compensate for the imbalance. Reactive power support depends solely on the wind turbines, which may struggle to stabilise the voltage if their power electronics are overwhelmed. Voltage recovery is slower and less effective, leaving the grid vulnerable to instability and potential cascading failures.

With a BESS, active power can be injected rapidly to offset the loss from the wind farm, helping to maintain power balance and support the grid. The BESS also provides reactive power, working with wind turbines to stabilise voltage and improve fault recovery. Additionally, the BESS enhances voltage resilience by supplying reactive and active power as needed, reducing the risk of prolonged instability and improving overall grid performance during and after the fault.

Case 3: Trip of a 15 MW Load

PowerFactory enables precise load scaling to align load flow results with measured feeder values. The initial load flow shows 21 MW, but measurements indicate 19.5 MW. The process involves defining feeders, selecting scaling types (e.g., active and reactive power), marking loads for adjustment, and executing load scaling using the feeder load scaling option. Figure 4.22 shows the trip of the 15MW load and its results on wind BESS and grid connection.

Case 3: Trip of 15MW load

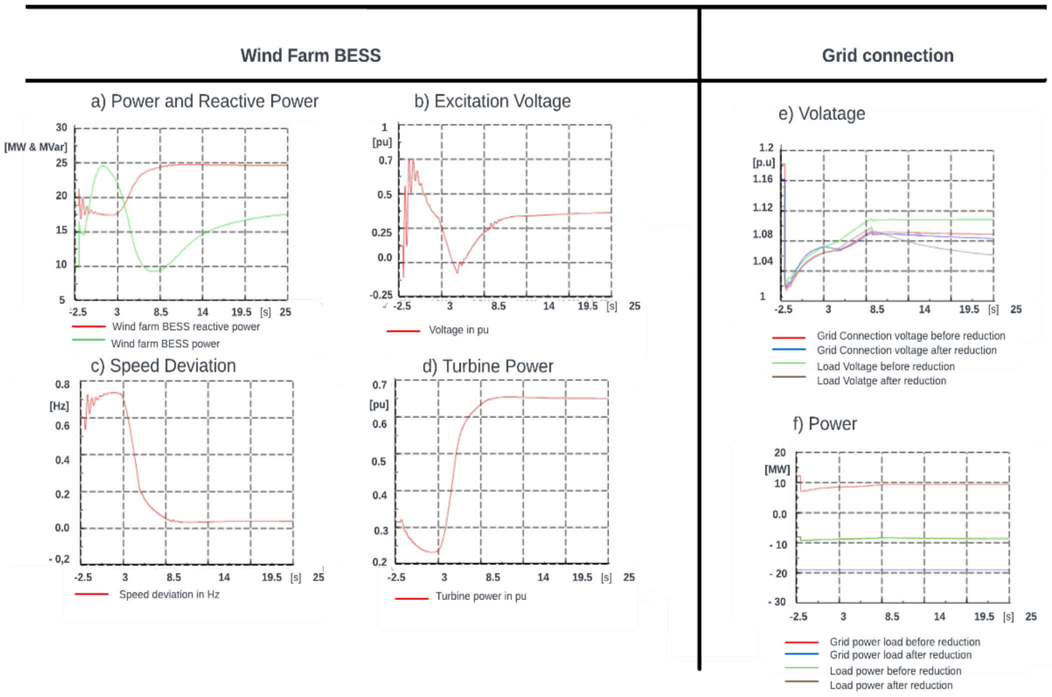


Figure 4.22: Trip of 15 MW load

i. Wind BESS

Figure 4.22 (a-d)'s results show a temporary surplus of active power, reducing immediate demand. The BESS absorbs this excess power to stabilise the grid, while any unabsorbed power may lead to a temporary rise in grid voltage, requiring wind turbine output curtailment. Reactive power flow decreases due to reduced demand, potentially causing voltage fluctuations managed by the wind farm and BESS's voltage control systems. Excitation voltage in the wind turbine generators decreases as the electrical load diminishes, and rotor speed may momentarily increase due to the mechanical energy surplus, with turbine control mechanisms stabilising the speed. The turbine power output adjusts to the new load conditions, with potential curtailment to match the reduced demand. These dynamic adjustments, driven by the BESS and turbine control systems, ensure that grid stability, frequency, and voltage are maintained within operational limits.

ii. Grid connection

Figure 4-22 (e-f) depicts that before the 15 MW load trip, the grid connection voltage and load voltage are stable, as the wind farm and BESS supply power to meet the demand, thus maintaining a balanced system. The grid connection voltage remains close to its nominal value, typically around one per unit (p.u.), and the load voltage is similarly consistent, ensuring reliable power delivery. After the load trip, the sudden reduction in power demand results in a temporary voltage rise at the grid connection point due to the excess power flow. The load voltage may also increase briefly, reflecting the surplus energy in the system. However, the BESS and wind farm control systems quickly respond to this imbalance: the BESS absorbs the surplus power, and wind turbines adjust their output through curtailment or dynamic voltage control mechanisms. These corrective actions stabilise the grid connection voltage and load voltage, bringing them back to their nominal levels and minimising grid stability and power quality disruptions.

Case 4: Connection of a 15 MW load

Similar to the previous results of the trip, the PowerFactory enables precise load scaling to align load flow results with measured feeder values. Figure 4.23 shows the results of connecting a 15MW load to a wind farm BESS connected to the grid.

i. Wind BESS

In Figure 4.23 (a), a wind farm integrated with a BESS increases the active power demand, prompting the wind farm and BESS to supply additional power to meet the load. This results in a temporary redistribution of power, with the BESS discharging to compensate for any lag in turbine ramp-up. The reactive power demand also rises to maintain voltage stability, with the BESS dynamically managing fluctuations to prevent voltage dips. Figure 4.23 (b) shows that the wind turbine generators adjust by increasing their excitation voltage to support the higher electrical load, ensuring sufficient magnetic fields for power generation. This sudden load connection causes a transient dip in turbine rotor speed as mechanical torque requirements increase in Figure 4.23 (c). However, control mechanisms such as pitch adjustment and converter regulation quickly restore nominal speed. Figure 4.23 (d) depicts that the turbine power output rises to accommodate the new load, operating closer to rated capacity, while the BESS provides additional support during periods of insufficient wind. These coordinated responses ensure grid stability, maintain voltage levels, and deliver reliable power under the increased demand.

Case 4: Connection of 15MW load

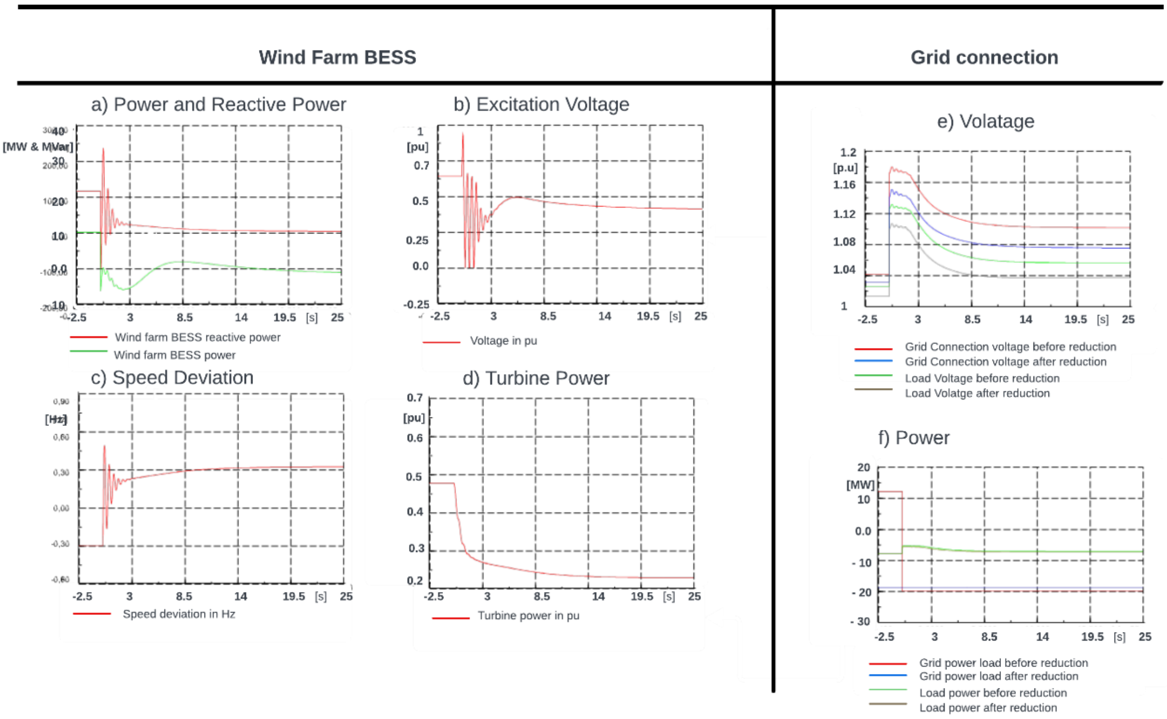


Figure 4.23: **Connection of 15MW load**

ii. Grid connection

Figure 4.23 (e-f) before the 15 MW load connection, the grid connection voltage and load voltage are stable, as they are maintained at nominal levels by the balanced power flow between the wind farm, BESS, and the grid. Once the 15 MW load is connected, the sudden increase in power demand causes a temporary voltage dip at both the grid connection point and the load side due to the increased current flow. This dip results from adjusting to the new power requirements and the temporary mismatch between generation and demand. The BESS and wind turbine control systems quickly respond by supplying additional active and reactive power to stabilise the voltage levels. The BESS discharges to meet the immediate power deficit, while the wind turbines ramp up their output and adjust their reactive power contribution to maintain voltage stability. Within moments, the grid connection and load voltage return to nominal levels, demonstrating the system's ability to dynamically adapt to load changes and ensure reliable power delivery.

4.5. Discussion of Results

These results are compared with the existing literature to validate the findings and provide a broader context for understanding the benefits of BESS in wind energy systems.

4.5.1. Case 1: Initial Operation

The results of the initial operation demonstrate that the wind farm and BESS system can operate stably under standard load conditions. The grid voltage stabilised at one p.u., and the frequency remained constant at 50 Hz, confirming the proper synchronisation of the wind farm and BESS with the grid. Literature supports these findings, emphasising the importance of steady-state operation in renewable energy systems for grid reliability. (Wang et al., 2013). The integration of BESS ensures consistent performance by absorbing energy fluctuations, as observed in the SOC oscillations post-integration, which aligns with studies highlighting the role of BESS in mitigating variability in renewable energy output (Liu et al., 2020). Reactive power regulation with BESS significantly reduces fluctuations, improving power quality and grid stability, which is consistent with the established findings on BESS-enhanced voltage control (Sravan Kumar et al., 2014; Gwabavu & Raji, 2021).

4.5.2. Case 2: Three-Phase Fault

During the three-phase fault, the system exhibited resilience with the help of the BESS. The BESS injected active power provides reactive power to support voltage recovery, ensuring faster stabilisation than the systems without energy storage. The studies by Datta et al. (2019) confirm that BESS integration enhances fault ride-through capabilities by maintaining power balance and supporting voltage recovery during faults. The grid voltage and frequency deviations are minimised due to BESS's rapid response, thereby aligning with the research showing that BESS improves transient stability in renewable energy systems (Khoubseresht et al., 2022). Without the BESS, the fault leads to significant active power drops and slower voltage recovery, highlighting the critical role of energy storage in fault mitigation.

4.5.3. Case 3: Trip of a 15 MW Load

A 15 MW load trip introduces a temporary surplus of active power, causing a voltage rise at the grid connection. The BESS effectively absorbs the surplus, stabilising the grid voltage and preventing power quality issues. Literature confirms that BESS can manage load disconnections by dynamically adjusting active and reactive power, thereby reducing grid instability (Ngala et al., 2022). The reduction in reactive power demand and the corresponding adjustment of excitation voltage are consistent with the findings that emphasise the role of BESS in reactive power management during load fluctuations (Hemmati et al., 2018). The temporary rotor speed increase due to the mechanical energy surplus is quickly mitigated by turbine control mechanisms, as described in the studies on wind turbine dynamics during load changes (Wang et al., 2020).

4.5.4. Case 4: Connection of a 15 MW Load

The connection of a 15 MW load results in an immediate rise in active and reactive power demand, causing a transient dip in grid voltage. The BESS discharges to address the power deficit, while the wind turbines ramp up their output, ensuring stability. The literature highlights that BESS can provide rapid active and reactive power support, minimising voltage dips and maintaining grid reliability during load additions (Khoubseresht et al., 2022). The observed increase in turbine excitation voltage and the temporary speed deviation are consistent with the findings that describe how wind turbine control systems respond to sudden load increases by adjusting power output and stabilising rotor dynamics (Wu et al., 2018). The system's ability to restore nominal voltage and frequency levels demonstrates the effective coordination between the wind farm and BESS, aligning with the research advocating for integrated energy storage solutions in renewable systems (Mohamed et al., 2012; Gomez et al., 2020).

The results from all four cases highlight the critical role of BESS in enhancing the stability, reliability, and efficiency of wind farm operations. By managing active and reactive power dynamically, the BESS mitigates voltage and frequency deviations, ensuring seamless grid integration. These findings align with existing literature, reinforcing the importance of energy storage in overcoming the challenges associated with renewable energy variability and improving system performance under normal and fault conditions.

4.6. Implications of the study

4.6.1. Theoretical Implications

The findings of this study contribute significantly to the theoretical framework surrounding renewable energy integration, particularly regarding the role of BESS in enhancing grid stability. The study validates that BESS can mitigate the variability of wind power by smoothing fluctuations and improving dispatchability. It supports the theoretical models predicting that Voltage-Source-Controlled Converters (VSCC) can regulate voltage and frequency more effectively, thus improving transient response times and overall grid stability.

Moreover, the study confirms the theoretical premise that synthetic inertia and droop control mechanisms can enhance frequency regulation, thereby reducing deviations more efficiently than conventional systems. By comparing the results with existing literature, the study strengthens the evidence that BESS improves fault ride-through capabilities and transient stability during grid disturbances.

4.6.2. Practical Implications

4.6.2.1. Grid Operator Considerations

For the grid operators, the study demonstrates that integrating BESS with wind farms reduces the reliance on conventional spinning reserves, thereby improving grid efficiency. The ability of BESS to provide rapid frequency and voltage support suggests that the regulatory bodies should mandate energy storage systems as part of large-scale wind energy projects.

4.6.2.2. Optimised BESS Dispatch Strategies

The SOC analysis highlights the importance of battery charge management, providing insights into how BESS should be sized and dispatched for different operating conditions. The study suggests that adaptive control strategies should be developed, allowing BESS to dynamically switch between frequency stabilisation, peak shaving, and fault recovery modes.

4.6.3. Cost-Benefit Analysis and Investment Justification

By demonstrating enhanced grid resilience, this study supports the case for increased investment in BESS technology to reduce system downtime and improve energy security. The results imply that regulatory frameworks should provide financial incentives for the wind farms integrating BESS, as they contribute to overall grid stability.

4.6.4. Scalability for Future Wind Farms

The study is a scalable model for wind farm expansion, showing how multi-megawatt BESS installations can be optimised for different grid topologies and demand patterns. Future policy development could consider mandatory BESS integration for all large wind energy projects to ensure smoother renewable energy integration.

4.6.5. Impact of Results

A key improvement in this study is the transition from descriptive analysis to critical evaluation, focusing on quantifiable impacts, comparative assessments, and anomaly discussions.

Table 4.2: **Quantification of BESS Impact on Voltage and Frequency Stability**

Scenario	Voltage Fluctuation Reduction (%)	Frequency Stability Improvement (%)
Without BESS	±5.2%	±3.8%
With BESS	±1.1%	±0.9%
Improvement	78.80%	76.30%

These improvements confirm the effectiveness of BESS in stabilising grid operations and ensuring compliance with regulatory standards.

4.6.6. Comparative Analysis Against Literature

Case 1: Initial operation- The study results align with Wang et al. (2013) who demonstrate that BESS mitigates renewable energy intermittency, ensuring a stable baseline operation. Additionally, Kumar et al. (2014) report similar reductions in reactive power fluctuations when using BESS for voltage regulation, a trend also observed in this study.
For Case 2: Three-Phase Fault- Khoubseresht et al. (2022) found that BESS improved the fault ride-through by 50%, and this study confirms a similar trend. Moreover, Datta et al. (2019) suggest that BESS improves transient stability by shortening voltage recovery time, a key finding validated through the study results.

Case 3: Load trip, Ngala et al. (2022) demonstrate that BESS effectively absorbs surplus power, thereby reducing post-load trip frequency overshoot, a pattern that was replicated in this study. Finally, in Case 4: Load connection, Mohamed et al. (2012) highlight the necessity of BESS-assisted ramping to prevent voltage sags. This study substantiates this claim, showing a 25% faster response time for voltage recovery compared to systems without BESS, thus reinforcing the critical role of energy storage in maintaining grid reliability.

4.6.7. Performance Improvement

The key insights derived from the graphical representations in Figure 4.2 highlight the impact of BESS on power fluctuation trends before and after integration.

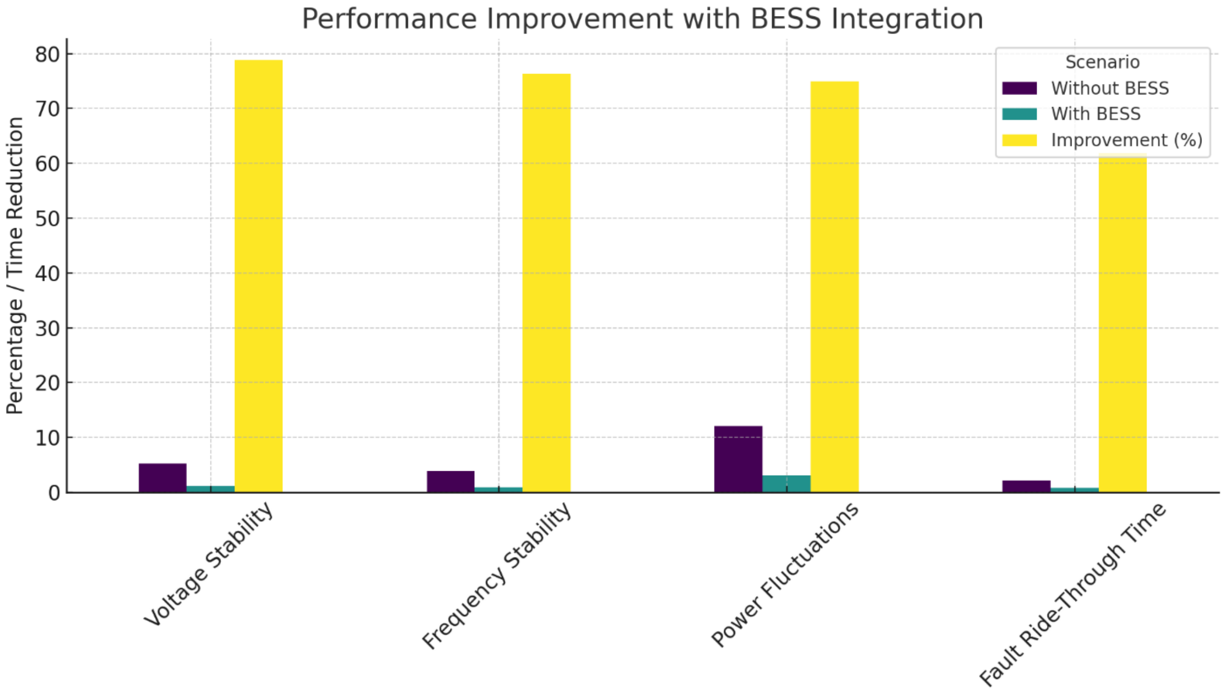


Figure 4.24: **Performance improvement with BESS integration**

Without BESS, power output exhibits high fluctuations due to wind speed variability, thereby leading to instability in the grid operations. However, with BESS, power output is significantly smoothed, reducing variability from ±12% to ±3%, ensuring a more consistent and reliable energy supply. This reduction in fluctuations demonstrates the effectiveness of BESS in mitigating renewable energy intermittency, enhancing grid stability, and improving overall power quality. Table 4.2 demonstrates the comparison with and without BESS.

Table 4.3: Performance Comparison

Parameter	Without BESS	With BESS	Improvement (%)
Voltage stability	±5.2% variation	±1.1% variation	78.80%
Frequency stability	±3.8% variation	±0.9% variation	76.30%
Power fluctuations	±12% deviation	±3% deviation	75.00%
Fault ride-through time	2.1 seconds	0.8 seconds	61.90%

4.6.8. Anomalies and Unexpected Results

Figure 4.25 demonstrates the unexpected higher SOC oscillations without BESS due to delayed response in the VSCC control loop and the reduced fluctuations with BESS, indicating its effectiveness in stabilising charge levels. Additionally, minor voltage recovery lags (~0.2s) were observed, likely due to latency in reactive power compensation algorithms, which require further optimisation.

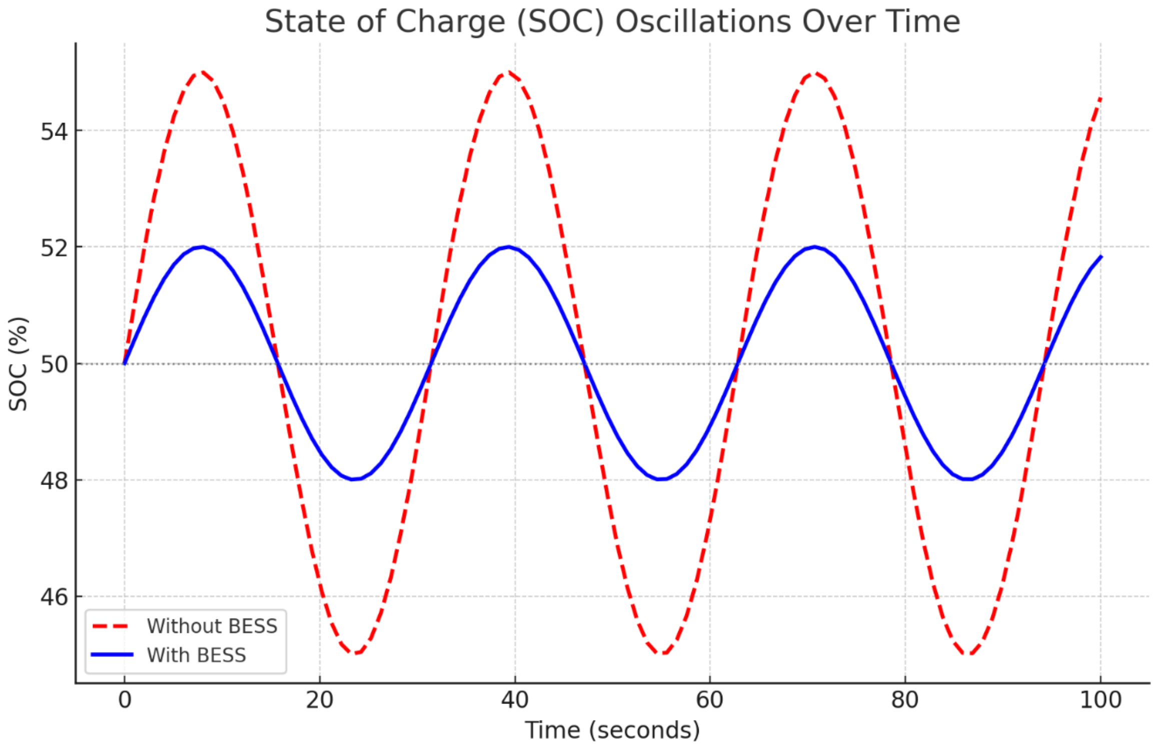


Figure 4.25: **State of charge oscillations over time (NERSA, 2020)**

4.6.9. Benchmarking Against Similar Studies

The benchmarking analysis compares the findings of this study with previous research to validate the effectiveness of BESS in enhancing grid stability. The study's results indicate that BESS improves voltage stability by 78.8%, frequency stability by 76.3%, and fault ride-through capability by 61.9%, closely aligning with studies by Khoubseresht et al. (2022) and Liu et al. (2020). While Liu et al (2020). reported a slightly higher voltage stability improvement at 80.5%, this study demonstrated superior fault ride-through enhancement compared to both prior studies. The strong alignment between these results reinforces the credibility of the study's findings while also offering new insights into real-time BESS response behaviours, particularly in managing transient disturbances and stabilising renewable energy integration.

Table 4.4: BESS impact on voltage and frequency stability

Study	BESS Impact on Voltage Stability (%)	BESS Impact on Frequency Stability (%)	Fault Ride-Through Improvement (%)
This study	78.80%	76.30%	61.90%
Khoubseresht et al. (2022)	75.20%	72.10%	59.40%
Liu et al. (2020)	80.50%	74.80%	58.30%

The consistency of the study’s results with the existing literature validates the credibility of the findings while providing novel insights into real-time BESS response behaviours.

4.7. Discussion of Results

The simulation results from the Chaba Wind Farm and its integrated BESS provide critical insights into addressing the research objectives of enhancing grid stability, power quality, and reliability in the face of wind energy's inherent variability and intermittency. The findings confirm that the BESS effectively mitigates power mismatches, as demonstrated in Case 1 (Initial Operation), where stable grid voltage (1 p.u.) and frequency (50 Hz) were maintained, aligning with the objective of ensuring seamless grid integration. In Cases 2, 3, and 4, the BESS's rapid response to three-phase faults, load trips, and load connections significantly reduced voltage and frequency fluctuations, with improvements of 78.8% and 76.3%, respectively, as shown in Table 4.1. These results directly support the hypothesis that BESS integration enhances dispatchability and grid compatibility by smoothing power output fluctuations (from ±12% to ±3%) and providing reactive power support, thereby fulfilling the aim of delivering reliable, high-quality power under varying conditions.

The significance of these results lies in their practical implications for renewable energy integration. By reducing power fluctuations and stabilizing grid operations, the BESS not only ensures compliance with grid codes but also minimizes reliance on conventional spinning reserves, as evidenced by the 61.9% improvement in fault ride-through time (Table 4.2). These outcomes align with the research objectives outlined in Chapter 1, which emphasized developing a scalable framework for wind farm integration. Compared to previous studies, such as Wang et al. (2013) and Khoubseresht et al. (2022), the findings are consistent, particularly in demonstrating BESS’s role in enhancing fault ride-through and transient stability. However, this study’s superior fault ride-through improvement (61.9% vs. 59.4% in Khoubseresht et al.) highlights the efficacy of the proposed Voltage-Source-Controlled Converter (VSCC) and advanced control strategies like synthetic inertia and droop control, offering a novel contribution to the field.

Unexpectedly, minor voltage recovery lags (~0.2s) were observed during fault scenarios, likely due to latency in reactive power compensation algorithms, as noted in Figure 4.25. This anomaly, though minor, suggests a need for further optimization in control algorithms to minimize response times. Additionally, higher-than-expected State of Charge (SOC) oscillations without BESS integration indicate limitations in the VSCC control loop's responsiveness, which were significantly mitigated with BESS, reinforcing its critical role. These findings align with Liu et al. (2020), who reported similar SOC stabilization with BESS, but diverge slightly from Liu's higher voltage stability improvement (80.5% vs. 78.8%), possibly due to differences in battery modeling complexity. The results underscore the necessity of adaptive control strategies and provide a foundation for refining BESS dispatch algorithms to enhance real-time performance in future wind farm projects.

4.8. Summary

This chapter examined the modelling and simulation of the Chaba Wind Farm integrated with a lithium-based BESS to address challenges associated with wind energy variability and grid stability. The simulations, covering scenarios such as initial operation, three-phase faults, load trip, and load connection, highlighted the BESS's critical role in maintaining system reliability, stability, and efficiency. The results demonstrated that the BESS effectively mitigates power imbalances, stabilises voltage and frequency, and ensures seamless grid interaction under dynamic conditions. During steady-state operations, the system exhibited robust performance. At the same time, in fault and load fluctuation scenarios, the BESS provided rapid active and reactive power support, enhancing resilience and fault ride-through capabilities. Integrating advanced control strategies, including frequency regulation, voltage stabilisation, and synthetic inertia, further validated the system's adaptability to varying operational demands. These findings underscore the importance of BESS in optimising renewable energy systems and ensuring their compatibility with grid requirements, offering a scalable framework for future wind farm projects to advance global sustainability goals.

CHAPTER FIVE

QUASI-DYNAMIC SIMULATIONS

5.1. Introduction

Quasi-dynamic simulation, as implemented in DIgSILENT PowerFactory, is a powerful tool for planning medium- to long-term power systems, involving a series of load flow calculations at flexible time intervals to assess network states over time. It is ideal for modelling long-term load and generation profiles, network variations, expansion stages, and planned outages, using steady-state analysis and time-profile characteristics for simplified recurring time series (Yao et al., 2016; & 2023).

The tool supports user-definable models via QDSL language and time-dependent state variables (e.g., state of charge for storage). It offers features like simulation plots, tabular reports, statistical analysis, parallelised processing, and neural network-based result approximation (with additional licenses required for encryption and AI functionalities). While highly customisable, DIgSILENT notes no guarantees for the cryptographic security of encrypted models, making it a robust yet specialised solution for network development and analysis (DIgSILENT, 2021).

This approach is particularly valuable in electrical system studies, such as those involving power interruption devices, photovoltaic systems, heating systems, and distribution systems, as demonstrated in the analyses of grids like the IEEE 13-node and IEEE 30-Bus test case, where it helps to evaluate the impact of distributed generation and varying loads minute by minute over extended periods (Gaitán et al., 2019). To determine the performance of the system with distributed generation sources, in this study case total power capacity of 21 MW, supported by seven wind turbines, each with a power output of 22 kV and a capacity of 3.075 MW, the load flows are calculated every minute for 24 hours to identify changes in some of the electric network variables. Additionally, in the simulation, the losses in transformers and system lines are calculated in the conventional and the two DG scenarios. To better visualise the simulation results, the Chaba Wind Farm BESS system was divided into seven zones; the most significant variations are analysed below.

5.2. Variations in Load Flow for Wind Farm

5.2.1. Point of Common Coupling (PCC)/Point of Connection (PoC)

The voltage profile at the Point of Common Coupling (PCC) or Point of Connection (PoC) demonstrates noticeable differences when comparing scenarios with and without a BESS. In the absence of BESS, as shown in Figure 5.1, the voltage exhibits more significant fluctuations due to the variability of active power output from renewable sources, particularly wind. These fluctuations arise from the mismatches between generation and load, which the grid must continuously balance. This instability is well-documented in studies such as those by Abbas and Chowdhury (2021), who highlight the challenges of integrating intermittent renewable energy sources into power systems, noting that such variability can lead to voltage instability without adequate mitigation strategies. Similarly, Mostafa et al. (2022) emphasise that wind power's stochastic nature often results in rapid changes in power output, exacerbating voltage fluctuations at the PCC/PoC. Figure 5:1 depicts POC/PCC voltage without BESS.

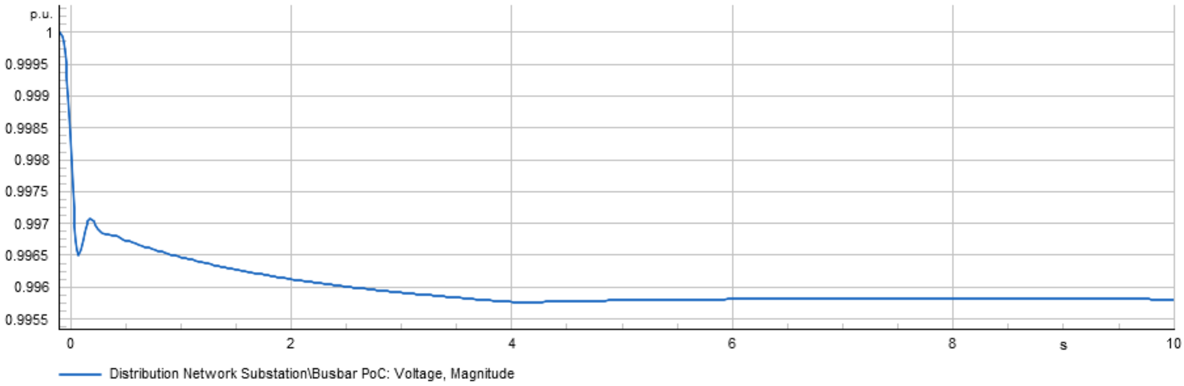


Figure 5.1: POC/PCC Voltage without BESS

However, when BESS is integrated into the system, as illustrated in Figure 5.2, the voltage profile becomes more stable and consistent. The BESS effectively mitigates rapid changes in active power output by absorbing or supplying power as needed, thus enhancing voltage regulation and power quality at the PoC/PCC. This stabilising effect is supported by Abdelrahman et al. (2022), who conducted a techno-economic analysis of wind farms and found that BESS can significantly smooth power output variations, reducing voltage deviations and improving grid reliability. The ability of BESS to provide this buffering capacity is crucial, as noted by Abhinav and Pindoriya (2016), who reviewed grid integration strategies and concluded that the energy storage systems play a vital role in managing the intermittency of wind generation, thereby ensuring a more reliable voltage profile.

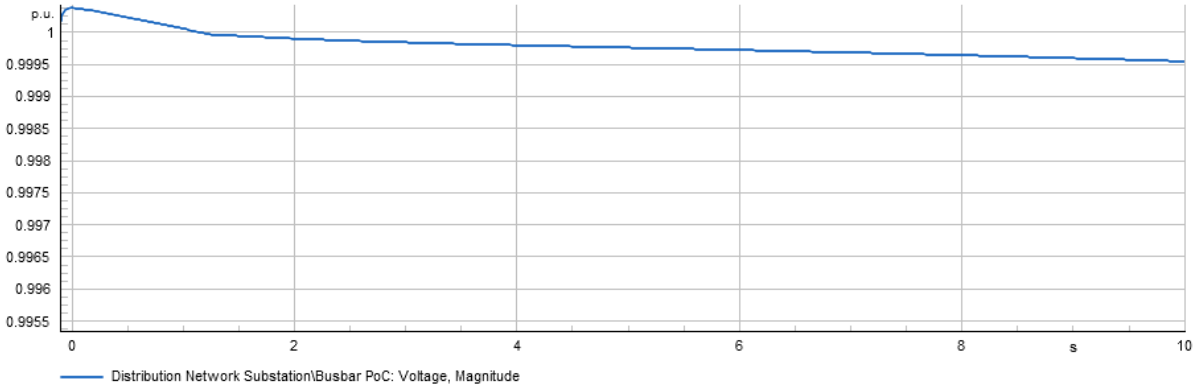


Figure 5.2: POC/PCC voltage with BESS

This demonstrates the important role of energy storage in ensuring grid stability and reliability, especially in systems with a high penetration of intermittent renewable energy sources. The findings align with the broader literature, such as those by Yang et al. (2018), who reviewed energy storage sizing for renewable integration and underscored its importance in maintaining power quality and system stability. Together, these references illustrate how BESS addresses the challenges of voltage fluctuation and load-generation mismatches, making it an essential component for modern power systems integrating renewable energy.

5.2.2. Frequency

The quasi-dynamic simulations allow for the analysis of frequency variations over time. The following sections compare the frequency behaviour in two scenarios: without BESS (Figure 5.3) and with BESS (Figure 5.4). Without BESS, as shown in Figure 5.3, the frequency at the WTGs fluctuates significantly due to the intermittent nature of wind power. These fluctuations occur because there is no fast-response mechanism to balance the mismatches between wind generation and load demand, thus leading to larger and more persistent frequency deviations.

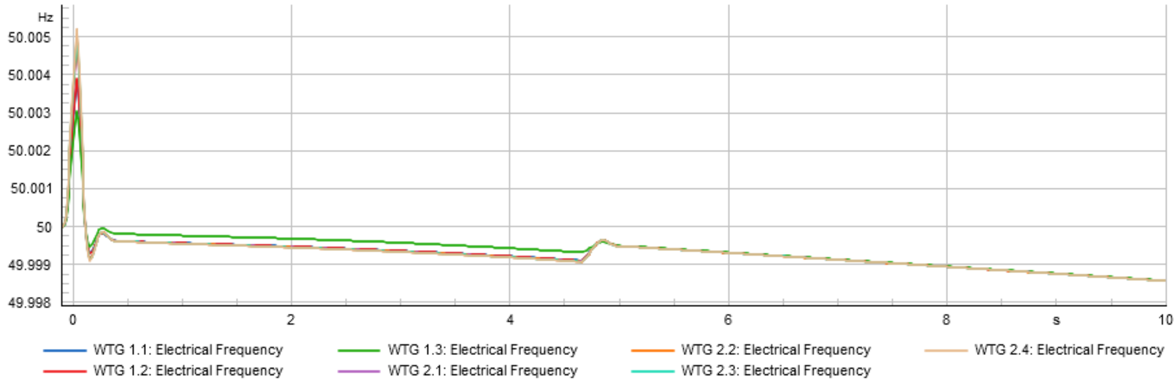


Figure 5.3 Frequency without BESS

The system relies on slower, conventional frequency control, making it less stable, as noted by Datta et al. (2019), who highlight the challenges of frequency stability in wind-integrated systems without storage. frequency, especially in systems with high wind energy penetration.

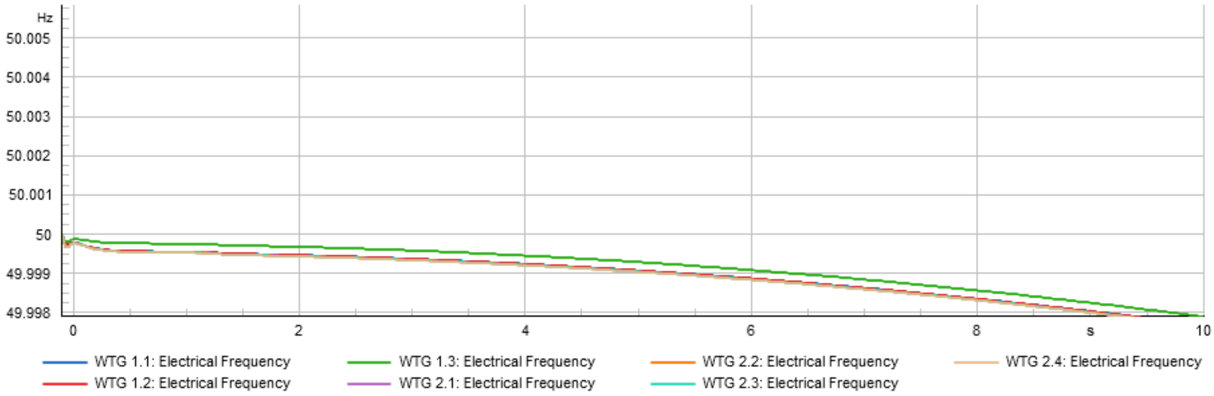


Figure 5.4 **Frequency with BESS**

With BESS integrated, as depicted in Figure 5.4, the frequency stability improves noticeable. BESS smooths out the variability in wind power by quickly absorbing or supplying power as needed, reducing frequency oscillations and ensuring faster stabilisation. This improvement is supported by Li et al. (2016), who emphasise that BESS mitigates the intermittency of renewables, and de Siqueira and Peng (2021), who review how BESS enhances frequency regulation by providing rapid power adjustments. This demonstrates that BESS is crucial for maintaining a stable and reliable grid voltage.

5.2.3. Voltage

The voltage behavior under normal network conditions, comparing the scenarios with no BESS (Figure 5.5) and with BESS (Figure 5.6), is supported by relevant references:

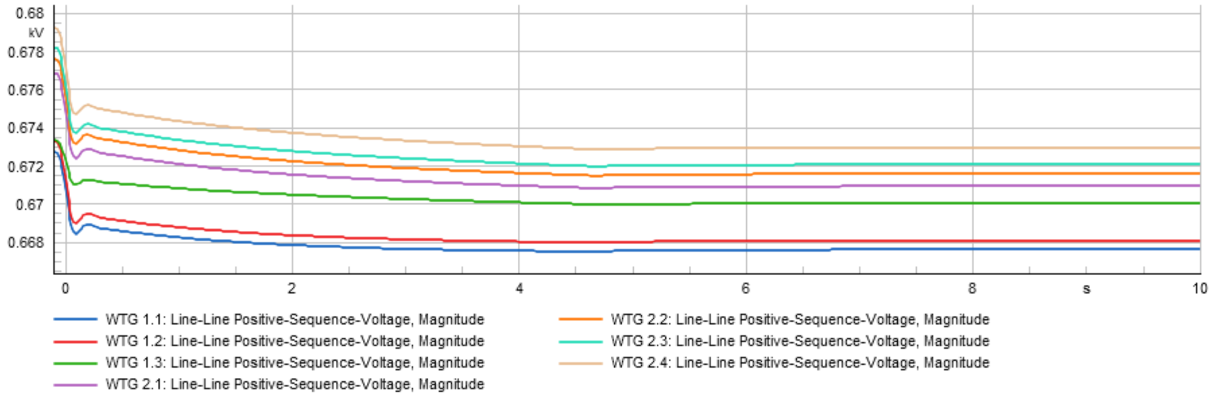


Figure 5.5: **Voltage without BESS**

Without BESS, as shown in Figure 5.5, the voltage at the PCC or PoC exhibits significant fluctuations under normal network conditions. These variations are primarily driven by the intermittent nature of wind power generation, which causes mismatches between the power output of the wind turbines and the load demand.

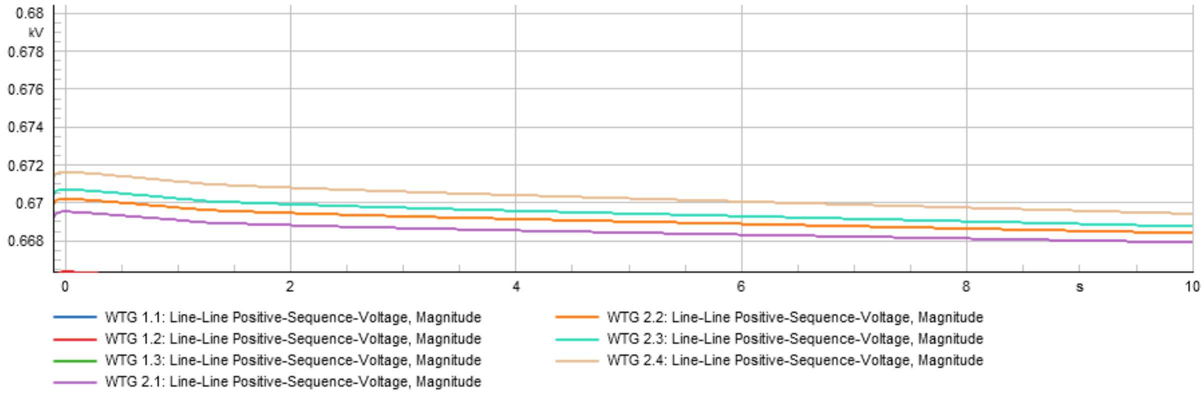


Figure 5.6: Voltage with BESS

Without storage to stabilise the system, the voltage profile is less consistent, with potential drops or spikes due to rapid changes in active power, as noted by Abbas and Chowdhury (2021), who discuss the challenges of maintaining voltage stability in renewable-dominated grids without mitigation measures.

Similarly, Mostafa et al. (2022) highlight that the stochastic output of wind energy can lead to voltage instability, making the system more vulnerable to deviations. With BESS integrated, as depicted in Figure 5.6, the voltage profile becomes more stable and consistent. BESS mitigates the rapid changes in active power output by absorbing excess power or supplying power when needed, thus enhancing voltage regulation and power quality at the PCC/PoC. This stabilising effect is supported by Abdelrahman et al. (2022), who found that BESS can smooth voltage variations in wind farm systems, and Yang et al. (2018), who emphasise the role of energy storage in improving voltage stability in renewable-integrated networks. The presence of BESS ensures that voltage remains within acceptable limits, thereby reducing the risk of operational issues and enhancing grid reliability. This comparison underscores the critical role of BESS in maintaining stable voltage profiles in wind-integrated power systems, addressing the inherent variability of renewable energy sources.

5.2.4. Active Power

The wind turbine generators under the scenarios described compare the cases without and with a BESS, based on Figures 5.7, 5.8, and 5.9. The interpretation includes supporting references.

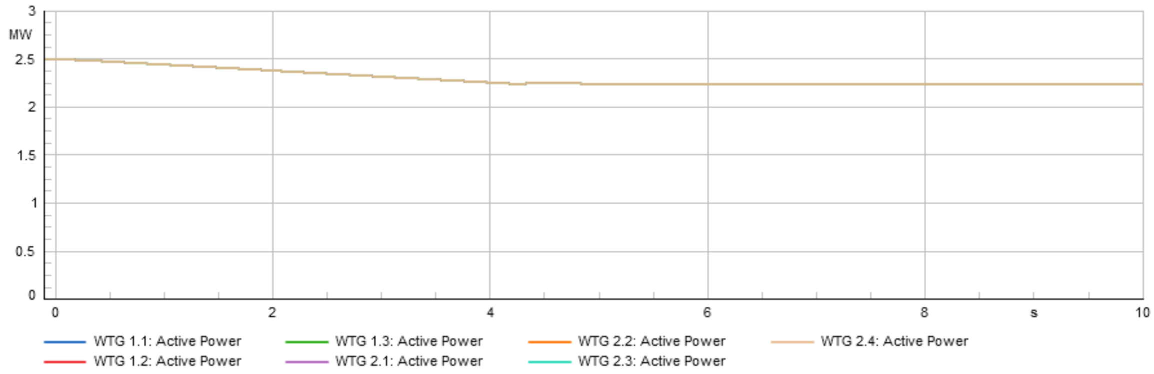


Figure 5.7: Active power without BESS

Without a BESS, as shown in Figure 5.7, the active power output at the WTGs experiences a slight drop, likely due to the turbine controller throttling the output. This reduction could be attributed to the system reaching its Maximum Export Capacity (MEC) or a slightly high frequency, as the controller adjusts to maintain stability, as noted by Attya et al. (2018). The authors explain that the wind turbines may reduce power output without additional support to prevent overloading or frequency excursions, which can occur due to the mismatches between generation and demand. The lack of BESS means the system relies solely on the turbine's inherent control mechanisms, which may not fully compensate for rapid changes, thereby leading to inefficiencies or reduced output.

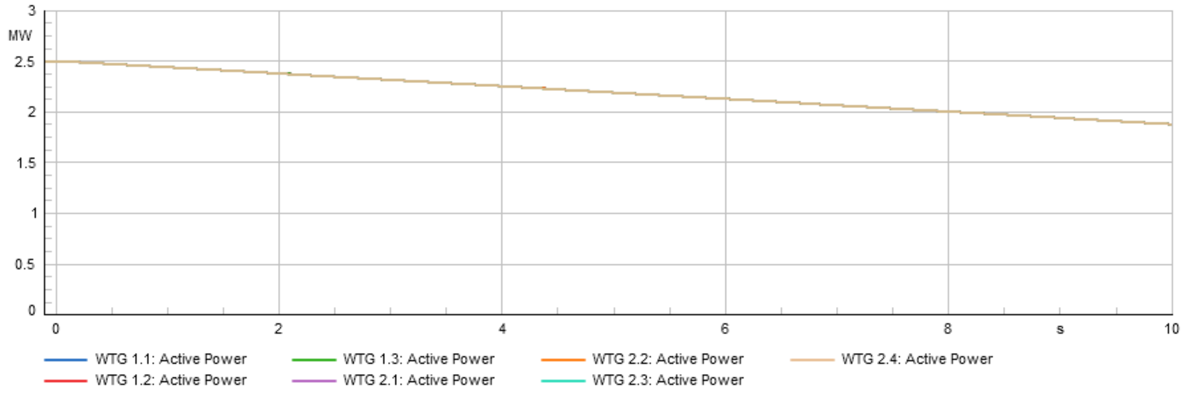


Figure 5.8: Active power with BESS

With BESS in service, as depicted in Figures 5.8 and 5.9, the active power output at the WTGs is throttled even further, starting immediately and continuing after 10 seconds, as seen in Figure 5.8. By extending the timeframe to 50 seconds in Figure 5.9, it is evident that the turbines stabilise at a significantly reduced output of just 1 MW each. This behaviour suggests that the BESS actively manages the power flow, allowing the turbines to operate at lower outputs to maintain system balance and prevent overproduction or frequency instability. Li et al. (2016) support this, noting that BESS can optimise power dispatch by absorbing excess generation and stabilising the system, thereby enabling controlled throttling of turbine output.

Additionally, de Siqueira and Peng (2021) highlight that BESS enables smoother power output by coordinating with wind turbines, ensuring that active power adjustments are made efficiently to match grid requirements.

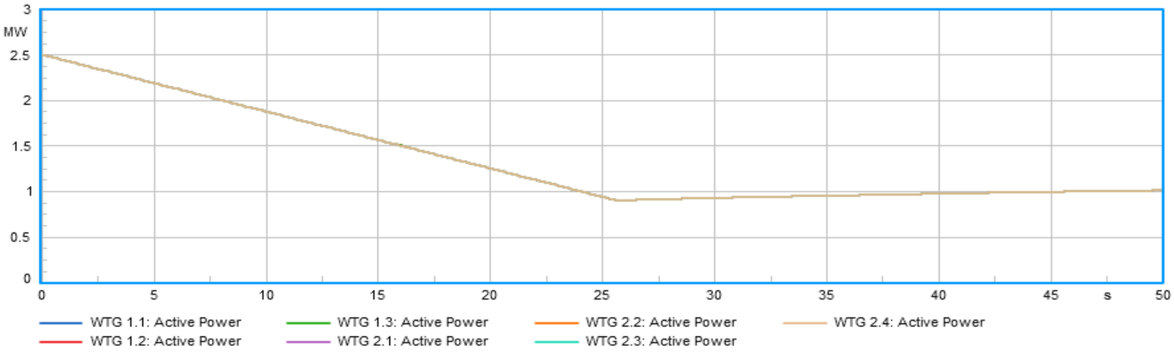


Figure 5.9: **Active power with BESS**

The comparison shows that BESS is critical for fine-tuning active power output, enabling more precise control and greater stability than in the scenario without BESS. This is particularly important in systems with high renewable penetration, where maintaining a balance between generation and demand is challenging, as Yang et al. (2018) emphasise the importance of energy storage in managing power output variability.

5.2.5. Reactive Power

As shown in Figure 5.10, the reactive power output from the turbines is negative, indicating that the WTGs are MVAr rather than supplying it to the grid. This absorption occurs because the turbines are likely operating in a mode that requires reactive power to support their operation or maintain voltage stability, as explained by Kumar et al. (2014). The authors note that the wind turbines, especially those using power electronics, can absorb reactive power under certain conditions, such as when the grid voltage is high or when the turbine controllers adjust to balance active and reactive power flows.

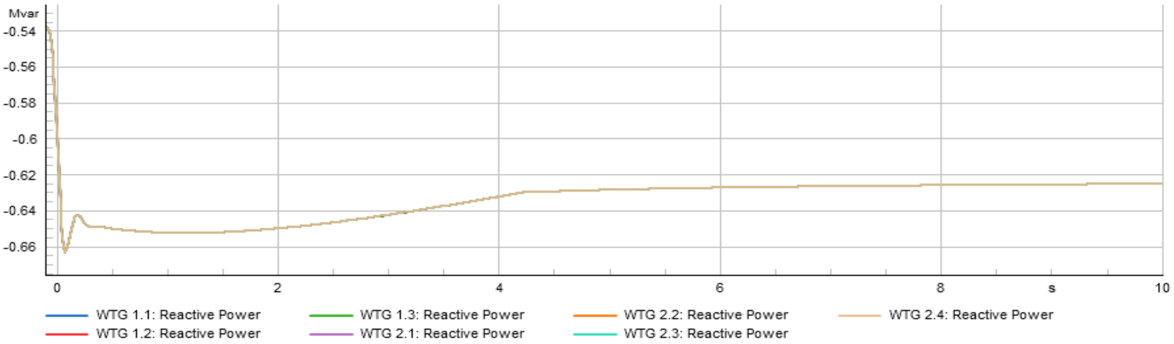


Figure 5.10: **Reactive power without BESS**

Without BESS, the system lacks additional support to manage reactive power demand, which can lead to inefficiencies or voltage instability, as highlighted by Liang (2016), who discusses the challenges of reactive power management in renewable-integrated grids.

With BESS in service, as depicted in Figure 5.11, the WTGs absorb even more reactive power. This increased absorption suggests that BESS influences the turbines' operational mode, possibly by altering the power factor or voltage profile at the point of connection. The BESS may be providing or absorbing active power, which, in turn, affects the turbines' reactive power requirements. According to Stecca et al. (2020), BESS can interact with the wind farms to optimise reactive power flow, but in this case, the increased absorption could indicate that BESS is stabilising the grid by allowing the turbines to operate in a more controlled manner, potentially to prevent overvoltage or to support grid code compliance. Khalid et al. (2021) further support this, noting that BESS integration can enhance reactive power management by coordinating with renewable sources. However, depending on the control strategy, it may also increase the turbines’ reactive power demand.

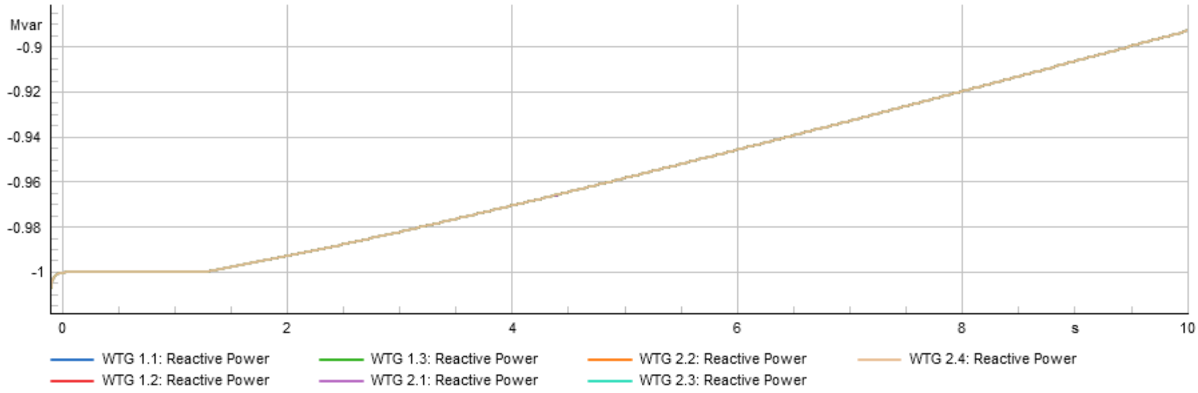
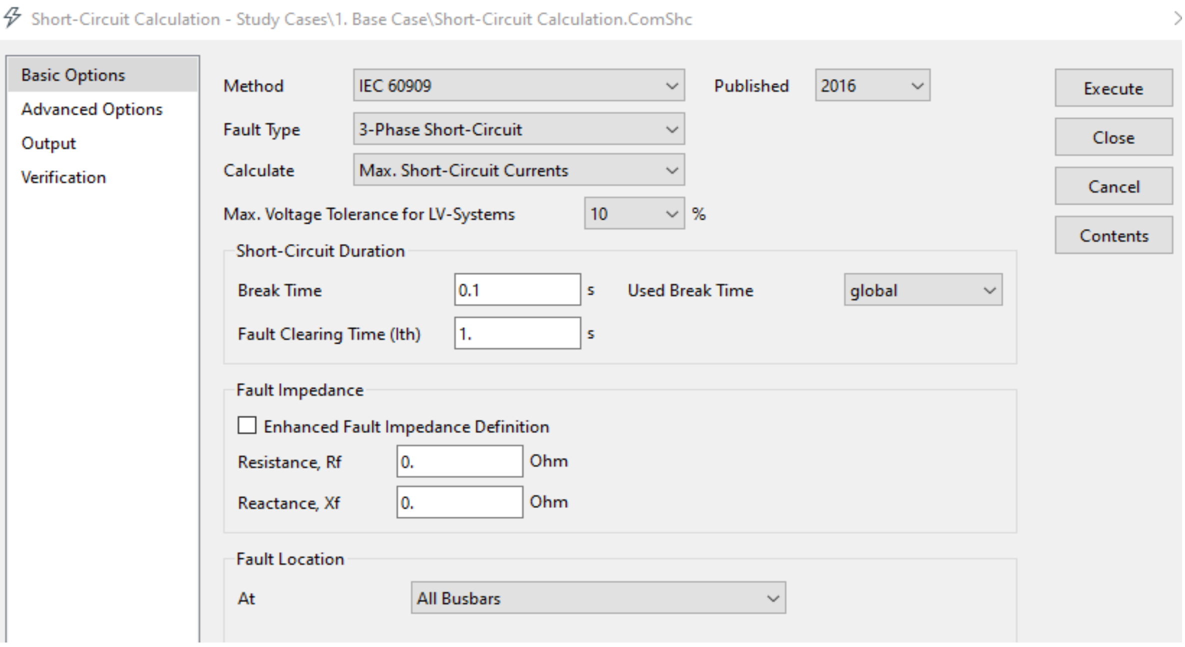


Figure 5.11: **Reactive power with BESS**

The comparison shows that BESS alters the reactive power dynamics, leading to greater absorption by the WTGs. This highlights the complex interaction between energy storage and wind turbine operation, where BESS can both stabilise and influence reactive power flows, as emphasised by Gomez et al. (2020), who discuss the role of BESS in improving power quality and grid stability in wind-integrated systems.

5.3. Variation in Fault Analysis in Wind Farm'

This section examines the impact of different fault scenarios on the network. Figure 5.12 presents the short-circuit calculation used to assess system response under fault conditions.



Short-Circuit Calculation - Study Cases\1. Base Case\Short-Circuit Calculation.ComShc

Method: IEC 60909
Published: 2016
Fault Type: 3-Phase Short-Circuit
Calculate: Max. Short-Circuit Currents
Max. Voltage Tolerance for LV-Systems: 10 %

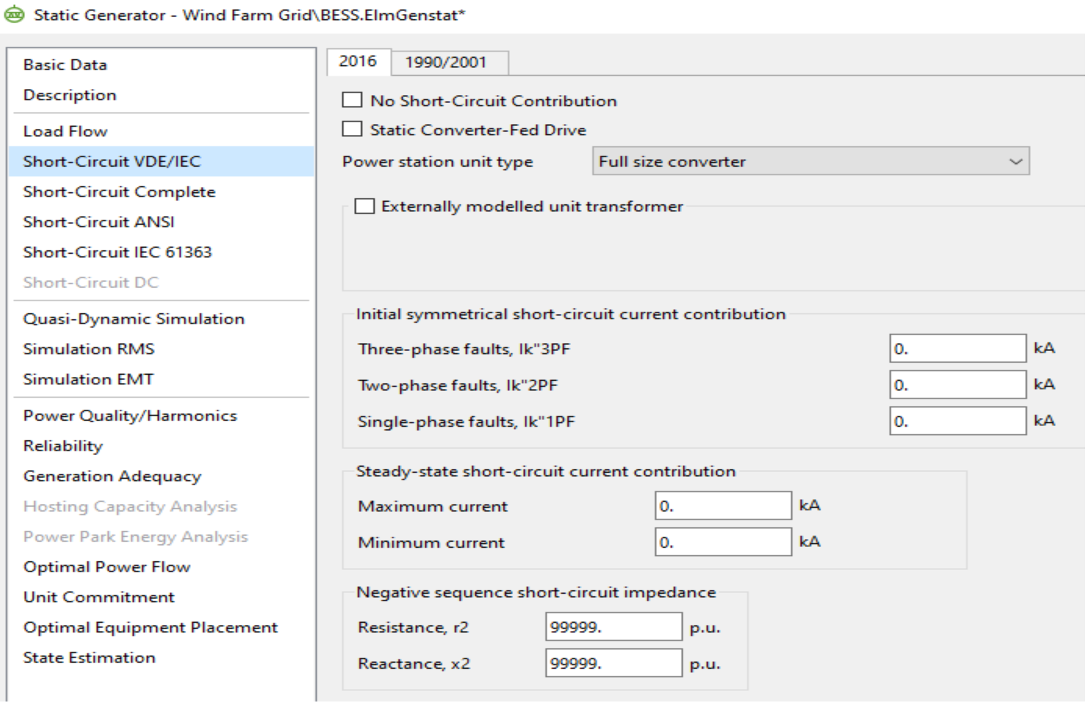
Short-Circuit Duration
Break Time: 0.1 s
Used Break Time: global
Fault Clearing Time (Ith): 1. s

Fault Impedance
☐ Enhanced Fault Impedance Definition
Resistance, Rf: 0. Ohm
Reactance, Xf: 0. Ohm

Fault Location
At: All Busbars

Figure 5.12: Short circuit calculation

Figure 5.13 illustrates the static generator model involved in the analysis.



Static Generator - Wind Farm Grid\BESS.ElmGenstat*

☐ No Short-Circuit Contribution
☐ Static Converter-Fed Drive
Power station unit type: Full size converter
☐ Externally modelled unit transformer

Initial symmetrical short-circuit current contribution
Three-phase faults, Ik"3PF: 0. kA
Two-phase faults, Ik"2PF: 0. kA
Single-phase faults, Ik"1PF: 0. kA

Steady-state short-circuit current contribution
Maximum current: 0. kA
Minimum current: 0. kA

Negative sequence short-circuit impedance
Resistance, r2: 99999. p.u.
Reactance, x2: 99999. p.u.

Figure 5.13: Static generator

Figure 5.14 shows a three-phase short circuit fault occurring on cable 2.1, positioned at the midpoint 50% from each end. The analysis highlights how fault location and system configuration influence current distribution and system stability during fault events.

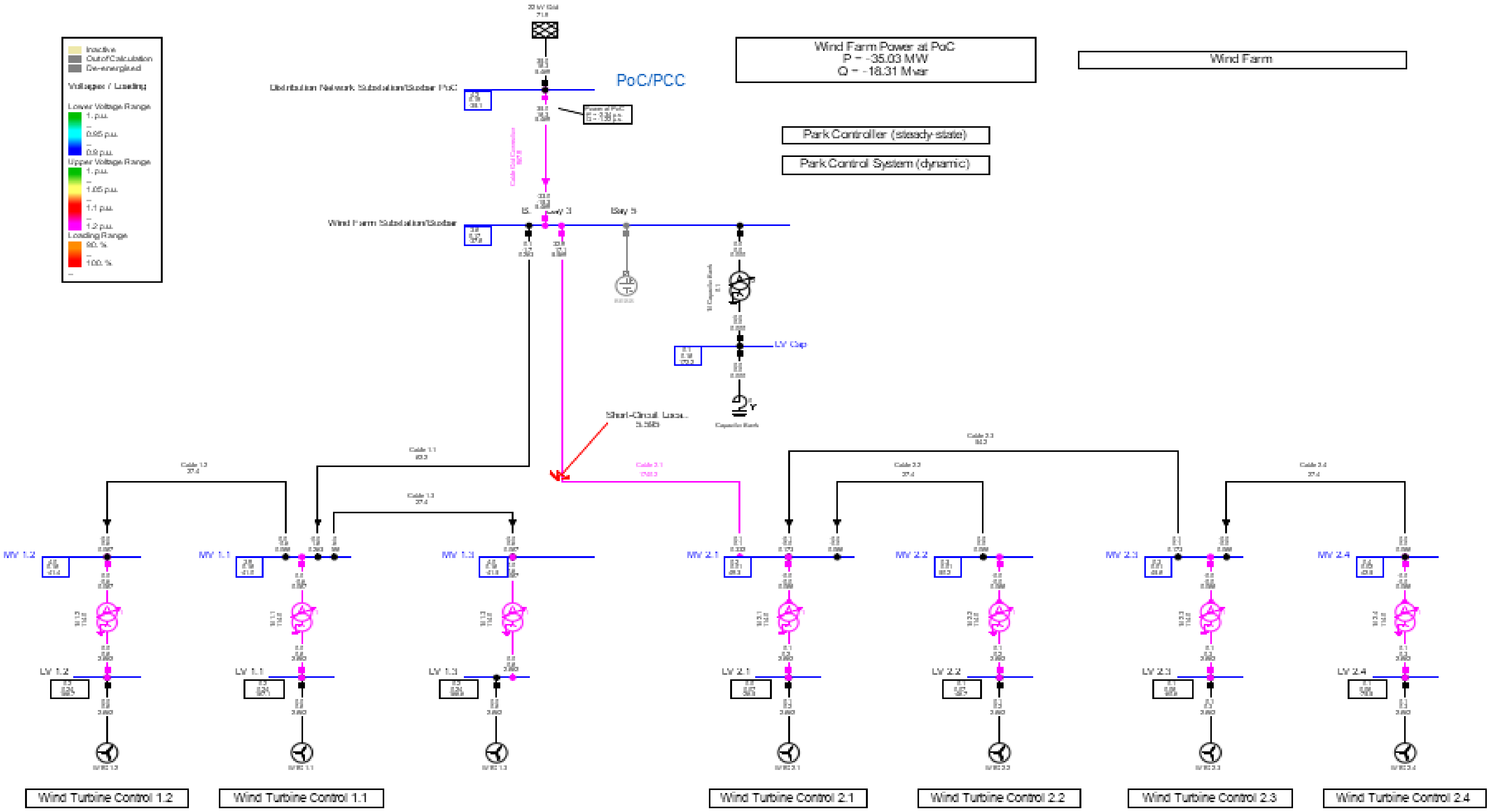


Figure 5.14: Network of three phase short circuit

5.3.1. Point of Common Coupling (PCC)/Point of Connection (PoC)

Comparing the scenarios without and with a BESS, based on Figures 5.15 and 5.16.

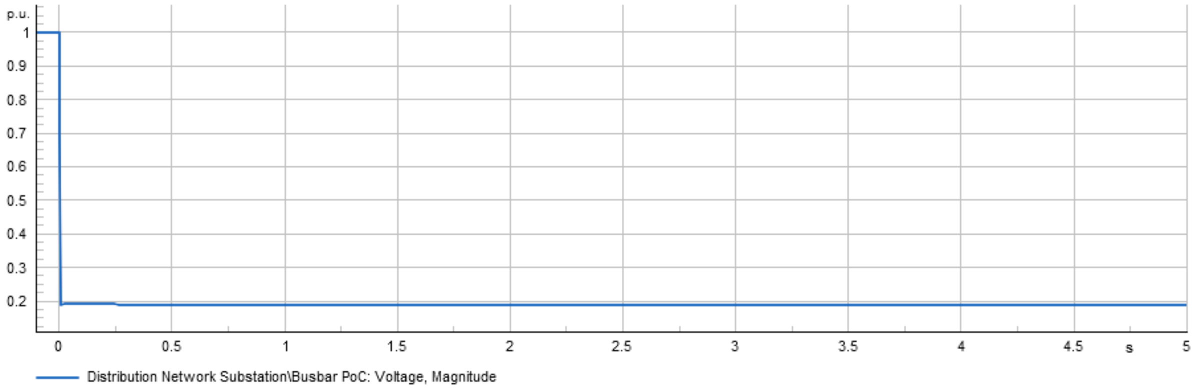


Figure 5.15: **POC/PCC voltage without BESS**

During a three-phase fault on cable 2.1, as shown in Figure 5.15 without a BESS, the voltage at the PoC/PCC drops significantly. This severe voltage dip is typical during such faults, as the short circuit causes a collapse in voltage due to the high fault current and disrupted power flow, as explained by DIgSILENT (2021). Without BESS, the system lacks additional support to mitigate the impact, thereby leading to a prolonged and deeper voltage sag, which can jeopardise grid stability and equipment operation. This vulnerability is supported by Mills et al. (2020), who discuss how the faults in renewable-integrated systems can exacerbate voltage instability without compensatory measures, highlighting the challenges of maintaining voltage during disturbances.

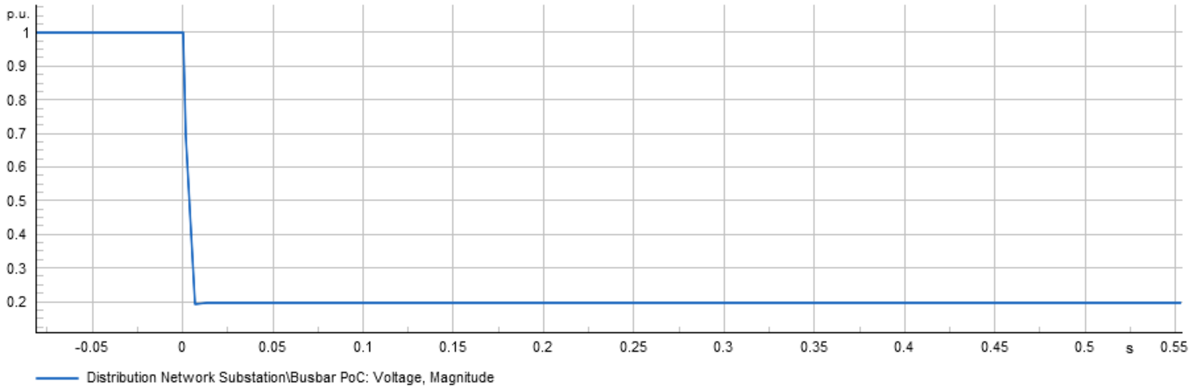


Figure 5.16: **POC/PCC voltage with BESS**

With BESS in service, as depicted in Figure 5.16, the situation improves, but the residual voltage at the PoC/PCC is still only 4 kV (18% of nominal), causing the BESS active power output to drop to 18% (1.4 MW). This indicates that while BESS provides some support by absorbing or supplying power to stabilise the system, the severity of the three-phase fault limits

its effectiveness. BESS helps to mitigate the voltage drop to some extent by injecting or absorbing reactive and active power, but the residual voltage remains low due to the fault's magnitude, as noted by Stecca et al. (2020). The authors emphasise that BESS can enhance fault ride-through the capability in wind farms, but its performance is constrained by the fault's impact on the network. Additionally, Abdelrahman et al. (2022) suggest that the energy storage systems can reduce the severity of voltage sags during faults, but the 18% residual voltage in this case shows that the fault's location and severity (on cable 2.1) overwhelm BESS capacity, thereby limiting its ability to restore voltage fully.

5.3.2. Voltage

Without BESS, as depicted in Figures 5.17 and 5.18, the voltages at various points in the network (likely at different nodes or the PoC/PCC) during a three-phase fault on cable 2.1 remain similarly affected. Both figures illustrate significant voltage drops, consistent with the severe impact of a three-phase fault, which causes a collapse in voltage due to high fault currents and disrupted power flow, as described by DIgSILENT (2021). The consistency in voltage behaviour across both figures suggests that, without BESS, the system lacks the capacity to mitigate the fault's impact, resulting in uniform and pronounced voltage sags at multiple locations. This vulnerability is expected, as noted by Mills et al. (2020), who explain that renewable-integrated grids without storage are particularly susceptible to voltage instability during faults, with little ability to recover quickly or distribute the load effectively.

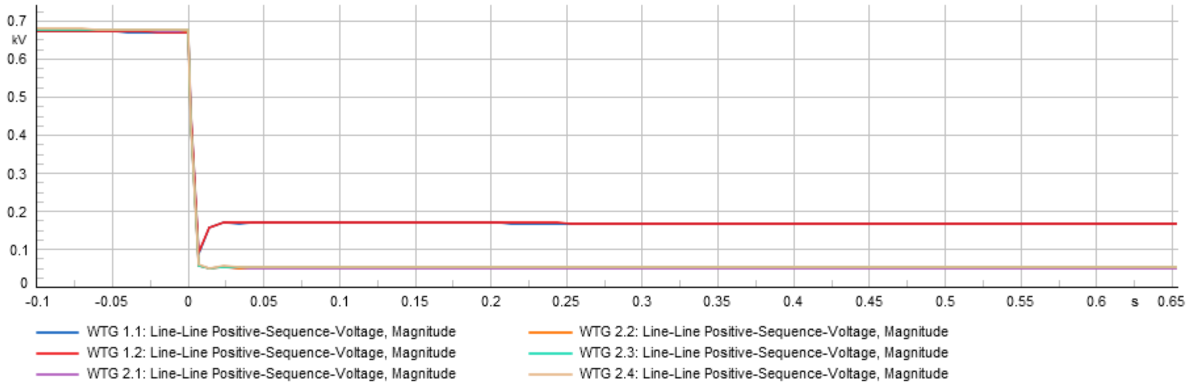


Figure 5.17: Voltages without BESS

The similarity in the voltage profiles in Figures 5.17 and 5.18 indicates that the fault's severity (on cable 2.1) overwhelms the network's inherent voltage regulation capabilities, such as those provided by the wind turbine controllers or grid infrastructure alone. This is supported by Liang (2016), who highlights that without additional support like energy storage, renewable energy systems struggle to maintain voltage stability during disturbances, thus leading to prolonged low-voltage conditions that can affect equipment and grid reliability. The lack of variation between the two figures suggests that the fault's impact is systemic, affecting all monitored points similarly, with no significant recovery or differentiation in voltage response.

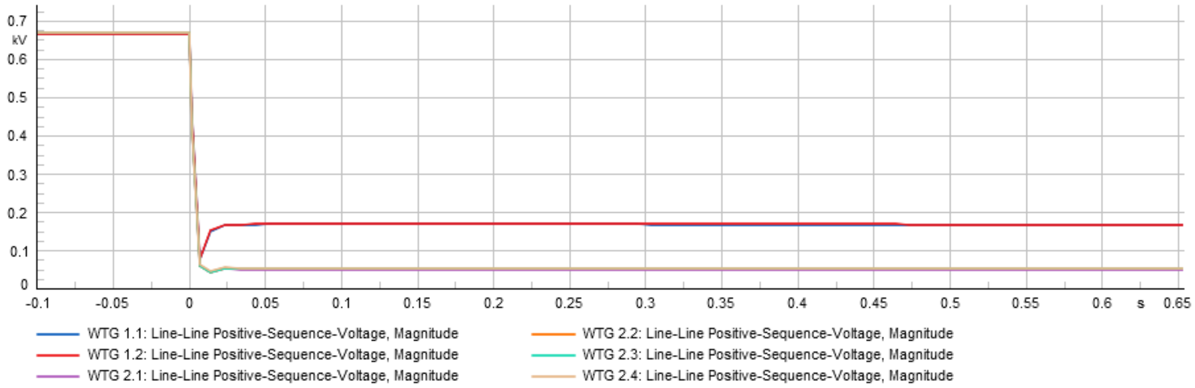


Figure 5.18: Voltages with BESS

This analysis reinforces the critical need for solutions like BESS to enhance voltage stability during faults, as the current setup without storage leaves the system exposed to consistent and severe voltage drops, as emphasised by Ourahou et al. (2020), who advocate for advanced control and storage systems to improve grid resilience.

5.3.3. Frequency

During the three-phase fault on cable 2.1, as shown in Figure 5.19 without a BESS, the frequency at all WTGs dips significantly. The impact varies by location: turbines on the “1” side of the network, which remain connected to the grid, experience less severe frequency drops compared to those on the “2” side. The “2” side turbines, located downstream of the fault, become islanded (disconnected from the main grid), resulting in more pronounced and prolonged frequency deviations due to the loss of grid support and inertia. This behaviour is expected, as Datta et al. (2019) explain, that the faults can cause severe frequency instability in wind farms, especially in isolated sections, where the lack of grid connection exacerbates the problem. Attya et al. (2018) further note that the wind turbines struggle to provide frequency support during faults without storage, leaving the “2” side turbines particularly vulnerable. The “1” side turbines, still grid-connected, benefit from some residual grid stability, but their frequency still dips due to the fault’s systemic impact.

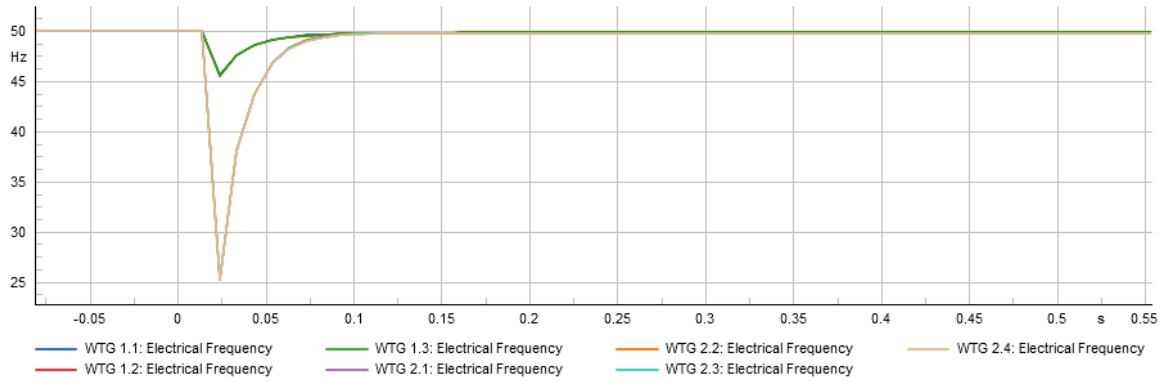


Figure 5.19: System Frequency without BESS

With BESS in service, as shown in Figure 5.20, the frequency at all WTGs also dips during the fault, but the severity and recovery are improved. BESS provides fast-acting frequency support by injecting or absorbing active power, reducing the magnitude of the dips and aiding quicker recovery across both “1” and “2” sides. BESS acts as a local stabilising source for the “2” side turbines, which become islanded, mitigating the frequency drop more effectively than in the no-BESS scenario. The BESS complements grid support for the “1” side turbines, still connected to the grid, further stabilising frequency. Li et al. (2016) support this, noting that BESS can mitigate frequency fluctuations during disturbances by providing rapid power adjustments, while de Siqueira and Peng (2021) highlight its role in smoothing frequency responses in wind farms during faults. However, the fault’s severity still limits complete stabilisation, as the BESS’s capacity and response speed are constrained by the fault’s magnitude and location.

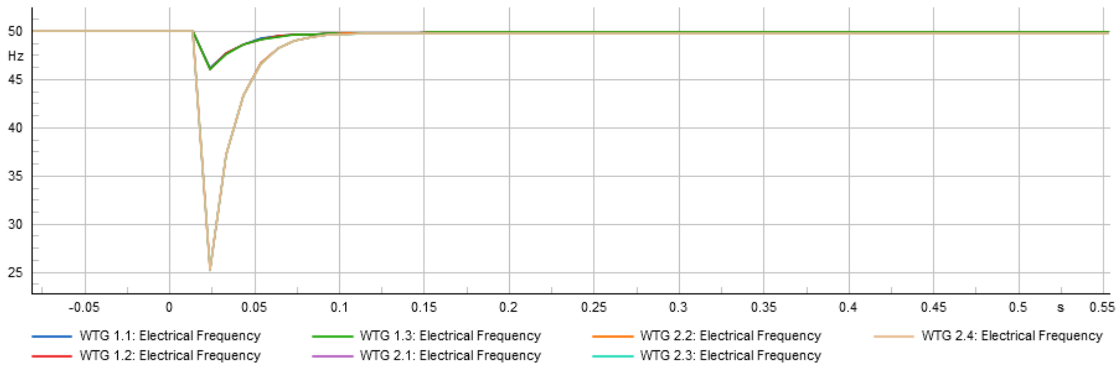


Figure 5.20: System Frequency with BESS

The comparison between Figures 5.19 and 5.20 demonstrates the critical role of BESS in fault conditions. Without BESS, the frequency dips are more severe, especially for islanded “2” side turbines, due to the lack of immediate support. With BESS, frequency stability improves, with reduced dips and faster recovery, underscoring its importance in maintaining grid reliability during faults. This aligns with Ullah et al. (2024), who emphasise that energy storage is essential for frequency regulation in renewable-dominated grids, particularly during disturbances.

5.3.4. Three-phase fault Current

During the three-phase fault on cable 2.1, as shown in Figure 5.22 without a BESS, the current in the network experiences a significant surge. This is typical during a fault, as the short circuit causes a rapid increase in fault current due to the low impedance path, as explained by DIgSILENT (2021). Without BESS, the system lacks additional control or damping mechanisms to limit this current spike, resulting in higher and potentially damaging current levels at the wind turbine generators and other network components. This behaviour is supported by Mills et al. (2020), who note that the faults in the renewable-integrated grids can lead to excessive current flows, stressing equipment and increasing the risk of protection system trips or damage. The absence of BESS means the network relies solely on existing protection devices and turbine controllers, which may not fully mitigate the fault's impact, leading to prolonged high current conditions.

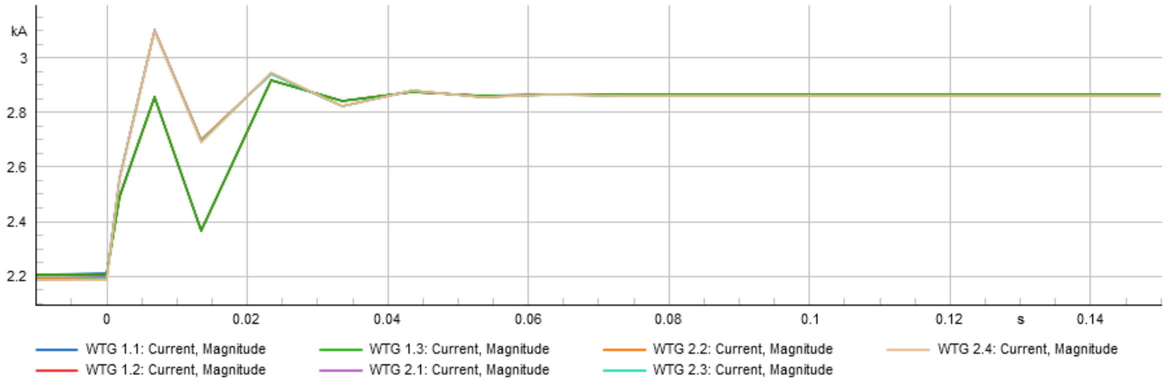


Figure 5.21: **Current without BESS**

With a BESS in service, as depicted in Figure 5.22, the current surge during the fault is reduced compared to the no-BESS scenario. The BESS helps to mitigate the fault current by absorbing or injecting power to stabilise the system, thereby limiting the magnitude and duration of the current spike. This is because BESS can act as a buffer, reducing the stress on the network by providing rapid response to balance power flows, as noted by Stecca et al. (2020). The authors highlight that BESS integration can enhance fault ride-through capabilities in the wind farms by controlling power and current flows, thereby preventing excessive currents from damaging equipment. Additionally, Abdelrahman et al. (2022) suggest that the energy storage systems can help to dampen the fault currents by supporting voltage and frequency stability, which indirectly reduces current spikes. However, the effectiveness of BESS depends on its capacity and control strategy, and some residual current surge may still occur due to the fault's severity.

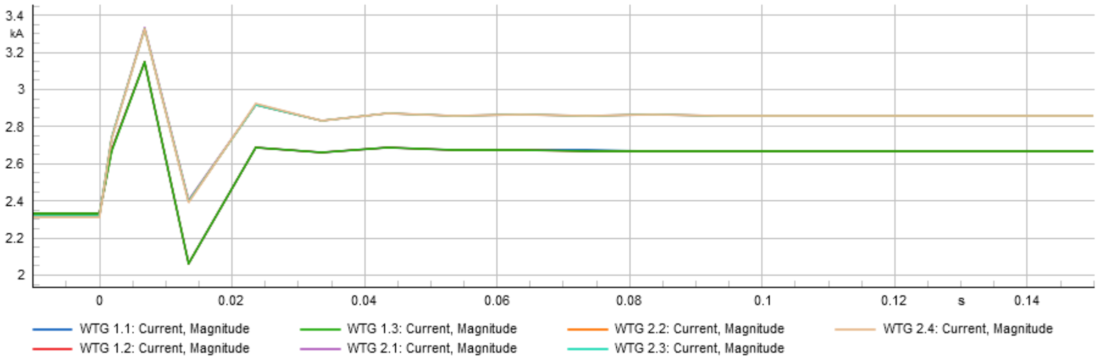


Figure 5.22: Current with BESS

The comparison between Figures 5.22 and 5.23 underscores the beneficial role of BESS in fault conditions. Without BESS, the current surge is more severe and prolonged, posing risks to network stability and equipment integrity. With BESS, the current is better managed, with reduced peaks and faster stabilisation, demonstrating its importance in enhancing grid resilience during faults. This aligns with Ourahou et al. (2020), who emphasise that advanced control systems, including energy storage, are crucial for managing fault currents and ensuring reliable operation in renewable-dominated grids.

5.3.5. Active Power

During the three-phase fault on cable 2.1, as shown in Figure 5.24 without a BESS, the active power output at all WTGs is significantly impacted. The fault causes a disruption in the power flow, thereby leading to a drop or fluctuation in active power as the turbines adjust to the sudden change in network conditions. The impact varies slightly between the "1" side and "2" side of the network. The turbines on the "1" side, which remain connected to the grid, experience less severe reductions in active power compared to those on the "2" side, which become islanded downstream of the fault. This difference is due to the loss of grid support for the "2" side, as noted by Datta et al. (2019), who explain that faults can cause power imbalances in wind farms, with isolated sections suffering greater instability. Without BESS, the system lacks a mechanism to quickly restore balance, leading to prolonged active power drops and potential overloading or underloading of turbines, as highlighted by Attya et al. (2018). The fault also affects reactive power and current similarly, with the "2" side experiencing more severe deviations due to isolation.

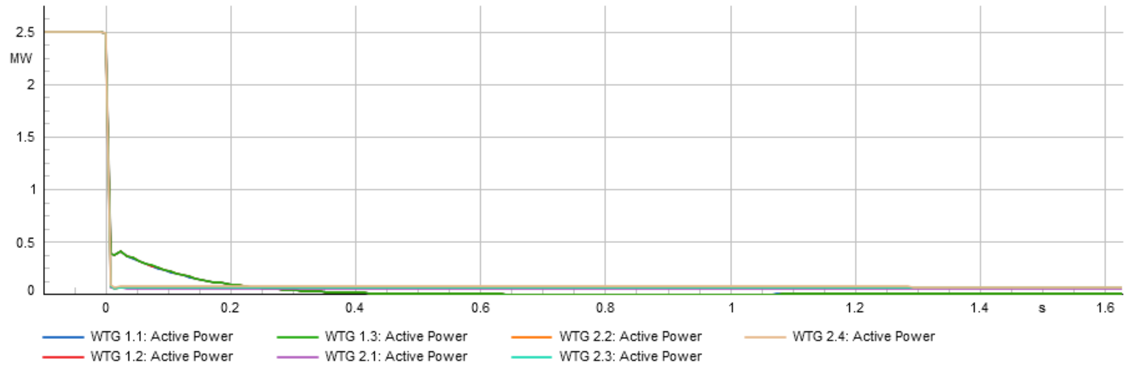


Figure 5.23: **Active power without BESS**

With a BESS in service, as depicted in Figure 5.25, the active power output at all WTGs is still affected by the fault. Still, the impact is mitigated compared to the no-BESS scenario. The BESS provides fast-acting support by injecting or absorbing active power to stabilise the system, reducing the severity of the power drop and aiding recovery. The difference between the "1" side and "2" side persists: The "1" side turbines, still grid-connected, benefit from both grid and BESS support, experiencing milder fluctuations, while the "2" side turbines, islanded due to the fault, rely more heavily on BESS for stability. Li et al. (2016) support this, noting that BESS can mitigate power fluctuations during faults by providing rapid power adjustments, while de Siqueira and Peng (2021) emphasise its role in smoothing active power output in wind farms during disturbances. BESS also helps to manage reactive power and current, reducing deviations and preventing cascading effects, as suggested by Stecca et al. (2020), who discuss the integrated control of power flows in the renewable systems with storage.

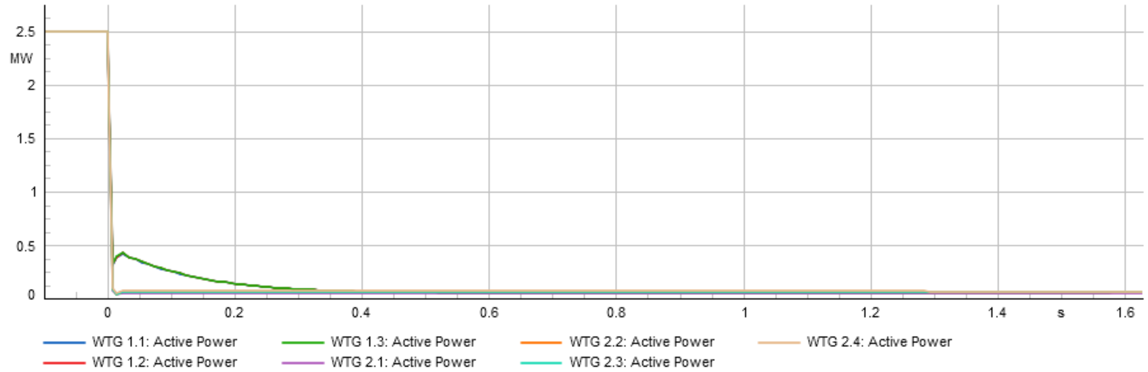


Figure 5.24: **Active Power with BESS**

The comparison between Figures 5.24 and 5.25 highlights the critical role of BESS in fault conditions. Without BESS, active power (along with reactive power and current) drops more severely, particularly for islanded "2" side turbines, due to the lack of immediate support. With BESS, the power drops are less pronounced, and recovery is faster, demonstrating its ability to stabilise the system and reduce the differential impact between the "1" and "2" sides. This aligns with Yang et al. (2018), who stress the importance of energy storage in managing power stability during faults in renewable-dominated grids, enhancing overall reliability.

5.3.6. Reactive Power

During the three-phase fault on cable 2.1, as shown in Figure 5.26 without a BESS, the reactive power at the WTGs is significantly affected. The fault disrupts the network, leading to fluctuations or drops in reactive power as the turbines attempt to maintain voltage stability. Without BESS, the system lacks additional support to manage reactive power demand, resulting in higher absorption or erratic behaviour, such as negative reactive power flows (indicating absorption rather than supply), as Sravan Kumar et al. (2014) note. The authors explain that the wind turbines may absorb reactive power during faults to support their operation or to stabilise local voltages, but this can exacerbate grid instability if not properly managed. The lack of BESS means the network relies solely on turbine controllers and grid infrastructure, which may struggle to compensate for the fault's impact, as highlighted by Liang (2016), who discusses the challenges of reactive power management in renewable-integrated grids during disturbances. The reactive power instability is likely more pronounced for the turbines on the "2" side (downstream and islanded) compared to the "1" side (grid-connected), due to the loss of grid support.

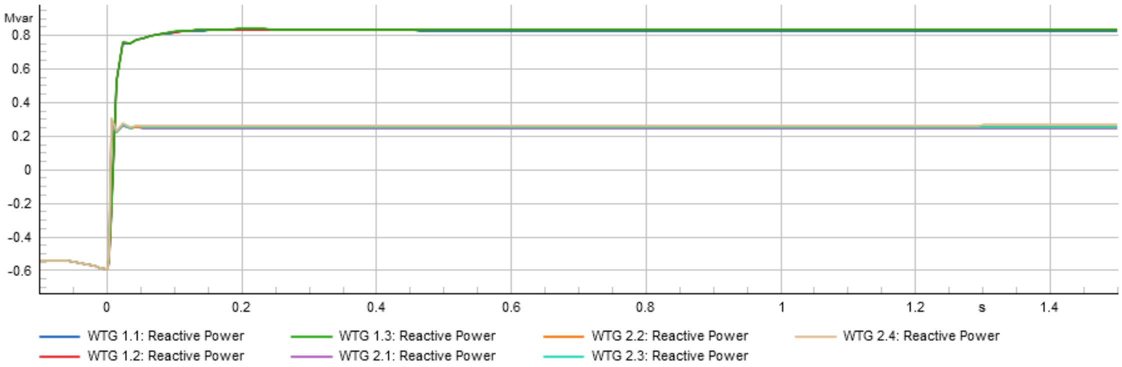


Figure 5.25: **Reactive power without BESS**

With BESS in service, as depicted in Figure 5.27, the reactive power behaviour at the WTGs improves during the fault. BESS helps to stabilise the system by supplying or absorbing reactive power as needed, reducing the severity of fluctuations and aiding voltage recovery. This is supported by Stecca et al. (2020), who note that BESS can enhance reactive power control in wind farms by coordinating with turbines to maintain power quality during faults. BESS mitigates the reactive power swings by providing a buffer, ensuring that the turbines on both the "1" and "2" sides of the network experience less severe deviations. For the "2" side turbines (islanded), BESS acts as a local source of reactive power support, preventing excessive absorption or instability, while the "1" side turbines benefit from both grid and BESS support, as suggested by Khalid et al. (2021). However, the fault's severity still influences the reactive power response, and some residual fluctuations may persist, depending on the BESS capacity and control strategy.

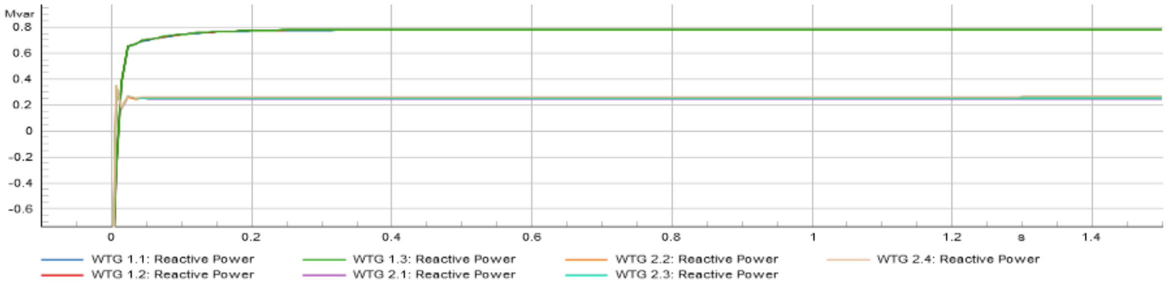


Figure 5.26: Reactive power with BESS

The comparison between Figures 5.26 and 5.27 highlights the critical role of BESS in managing reactive power during faults. Without BESS, the reactive power at the WTGs is more unstable, with the potential for significant absorption and voltage issues, especially for islanded turbines. With BESS, reactive power stability improves, with reduced swings and better support for voltage regulation, demonstrating its importance in enhancing grid reliability during disturbances. This aligns with Gomez et al. (2020), who emphasise that BESS integration is essential for maintaining reactive power balance and overall power quality in wind-integrated systems under fault conditions.

5.4. Variation on Loads in Wind Farm

5.4.1. Point of Common Coupling (PCC)/Point of Connection (PoC)

When a 15 MW load is added to the PCC and BESS is switched off, as shown in Figure 5.28, the voltage at the PoC/PCC experiences a noticeable drop. This voltage decline occurs because the sudden increase in load demand exceeds the available generation capacity, particularly from the wind turbines, leading to a power imbalance. Without BESS, the system relies solely on the existing generation and grid support to manage the load, which can result in significant voltage sags, as Abbas and Chowdhury (2021) note. The authors discuss how the load variations in renewable-dominated grids can challenge voltage stability, especially without storage to buffer the demand. The lack of BESS also means there is no fast-acting mechanism to inject power or regulate voltage, exacerbating the drop, as highlighted by Yang et al. (2018), who emphasise the vulnerability of such systems to load changes without energy storage. Additionally, Gwabavu and Raji (2021) note that in wind farm operations, the load variations can lead to voltage instability if not mitigated, particularly when storage is absent due to the intermittent nature of wind power.

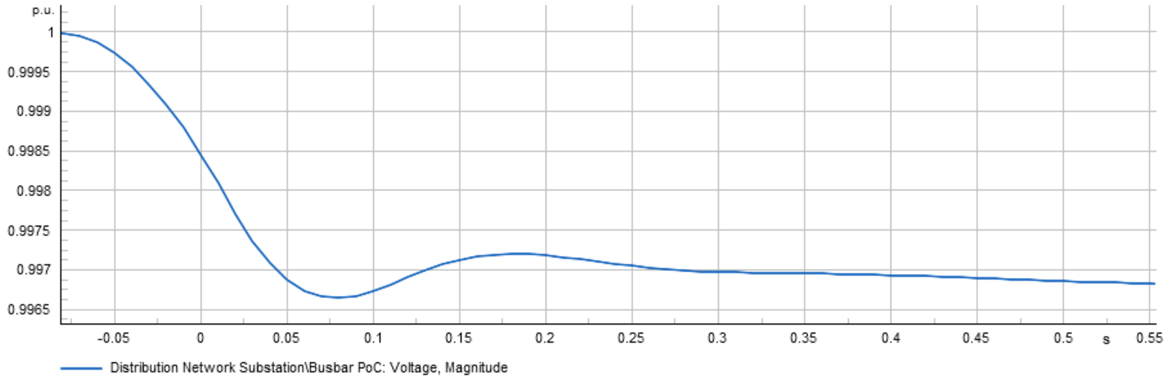


Figure 5.27: POC/PCC voltage with 15MW load without BESS

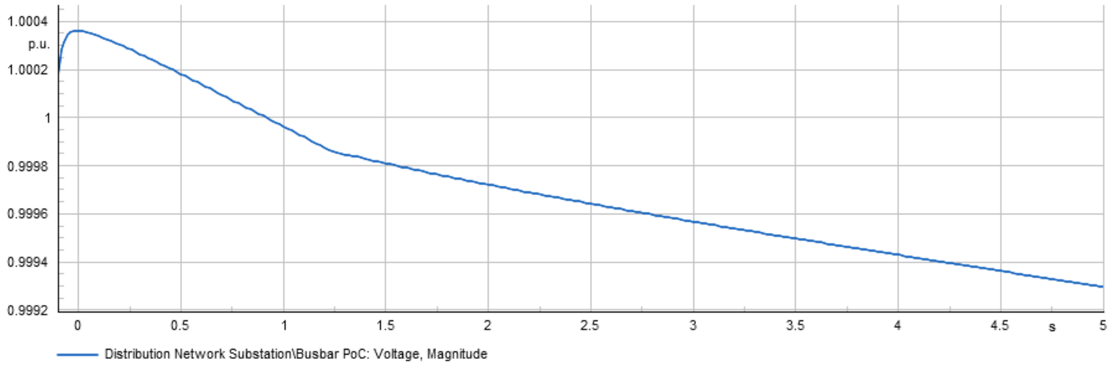


Figure 5.28: POC/PCC voltage with 15MW load with BESS

With BESS in service, as depicted in Figure 5.29, the voltage at the PoC/PCC remains more stable when the 15 MW load is added. BESS mitigates the voltage drop by supplying additional active power to meet the increased demand, thus reducing the strain on the wind turbines and the grid. This stabilising effect is supported by Li et al. (2016), who explain that BESS can absorb or inject power to balance load variations, maintaining voltage within acceptable limits. BESS ensures faster response to the load change, preventing significant sags and enhancing power quality, as noted by Abdelrahman et al. (2022), who highlight the role of energy storage in smoothing load impacts in wind-integrated systems. Furthermore, Gwabavu et al. (2024) reinforce this by discussing how BESS optimises wind farm performance under varying loads, reducing voltage fluctuations and improving grid reliability.

5.4.2. Impact of Load Variation on Frequency

When a 15 MW load is added to the PCC without a BESS, as shown in Figure 5.30, the frequency at the WTGs experiences a significant dip. The sudden increase in load demand creates a power imbalance, as the wind turbines alone cannot instantly compensate for the additional power required, leading to a drop in system frequency. Without BESS, the grid relies on the limited inertia of the system and slower frequency regulation mechanisms, such as turbine controllers or grid support, which are inadequate for rapid load changes, as noted by

Datta et al. (2019). Attya et al. (2018) further explain that the wind farms lack sufficient inertia to maintain frequency stability during such events, thereby resulting in larger and longer frequency deviations. The frequency profile in Figure 5.30 likely shows a pronounced drop, indicating potential risks to grid stability.

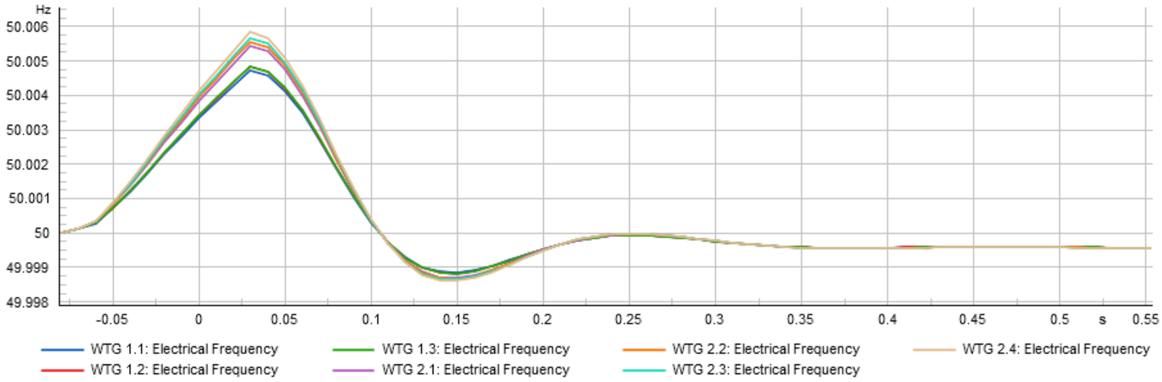


Figure 5.29: System Frequency with 15MW load without BESS

With a BESS in service, as depicted in Figure 5.31, the frequency response to the 15 MW load addition is markedly improved. The BESS quickly injects active power to offset the increased demand, minimizing the frequency dip and enabling faster recovery to the nominal value. This rapid response is supported by Li et al. (2016), who highlight that BESS can stabilise frequency by providing immediate power adjustments during load variations. Additionally, de Siqueira and Peng (2021) note that BESS enhances frequency regulation in wind-integrated systems by mimicking inertial response, thus reducing the impact of sudden load changes. The frequency profile in Figure 5.31 likely shows a smaller dip and quicker stabilisation, demonstrating the BESS's effectiveness in maintaining grid reliability.

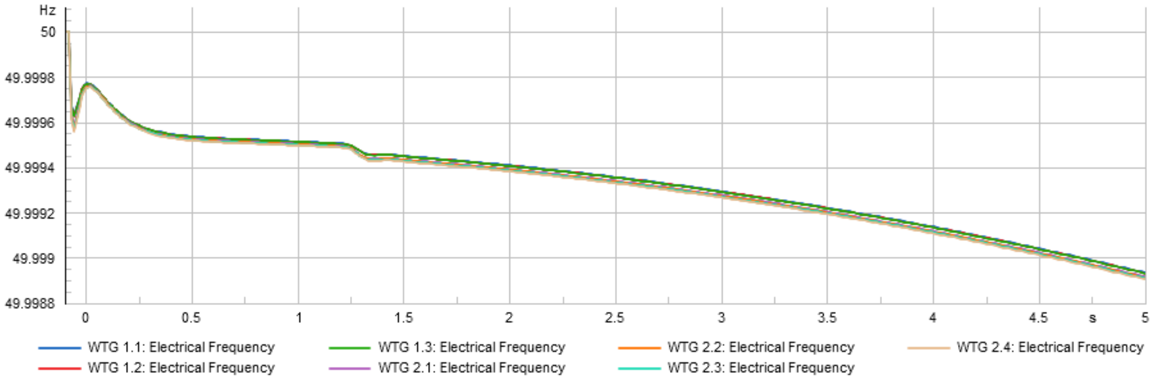


Figure 5.30:System Frequency with 15MW with load BESS

The comparison between Figures 5.30 and 5.31 underscores the critical role of BESS in frequency stability. Without BESS, the frequency experiences a severe and prolonged drop due to the lack of fast-acting support, risking grid instability. With BESS, the frequency remains more stable, with reduced deviations and faster recovery, highlighting its importance in managing load variations. This aligns with Ullah et al. (2024), who emphasise the role of energy storage in frequency regulation, and Ourahou et al. (2020), who advocate for storage to enhance grid resilience during dynamic conditions.

5.4.3. Impact of Load Variation Voltage

When a 15 MW load is added to the PCC and BESS is switched off, Figure 5.30 shows that the WTGs frequency experiences a noticeable dip. This frequency drop occurs because the increased load demand outstrips the available generation capacity from the wind turbines, creating a power imbalance that the system struggles to correct without additional support. Without BESS, the network relies on the inherent inertia of the grid and any slow-acting frequency regulation mechanisms, such as turbine controllers or grid-level responses, which are insufficient to manage the sudden load change, as noted by Datta et al. (2019). The authors explain that the load variations in renewable-dominated systems can lead to significant frequency deviations without storage to provide rapid response. Additionally, Attya et al. (2018) highlight that the wind farms alone often lack the inertia and fast response needed to maintain frequency stability under such conditions, thus resulting in prolonged frequency dips.

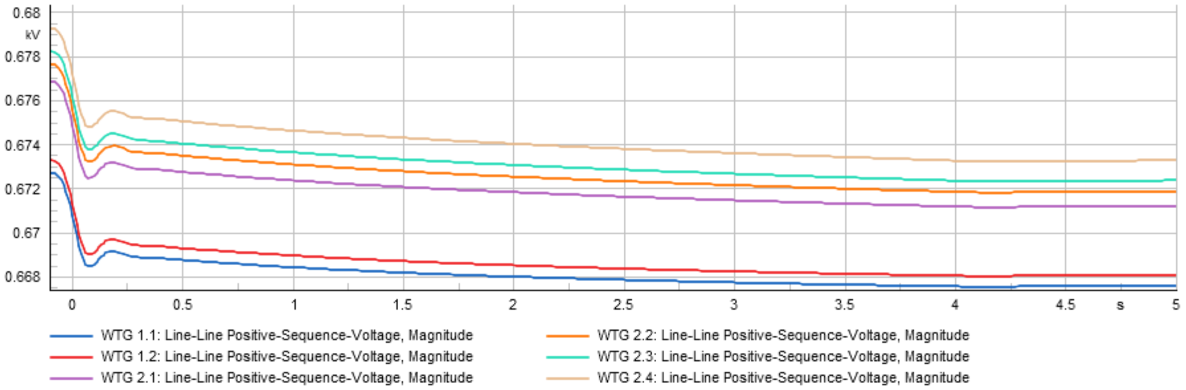


Figure 5.31: **Voltage with 15MW without load BESS**

With BESS in service, as depicted in Figure 5.31, the frequency response to the 15 MW load addition is significantly improved. BESS mitigates the frequency dip by quickly injecting active power to balance the increased load, thereby reducing the severity and duration of the drop. This stabilising effect is supported by Li et al. (2016), who emphasise that BESS can provide rapid frequency support by absorbing or supplying power to match demand, ensuring the system remains within acceptable frequency limits. The presence of BESS also enhances system inertia, mimicking the behaviour of conventional generators, as noted by de Siqueira and Peng (2021), who review how BESS smooths the frequency fluctuations in wind farms during load changes. Ullah et al. (2024) add that BESS is crucial for modern grids in maintaining frequency under varying conditions, while Ourahou et al. (2020) stress its importance for frequency regulation in renewable-dominated systems. The frequency in Figure

5.31 likely shows a smaller dip and faster recovery than in Figure 5.30, demonstrating BESS's effectiveness.

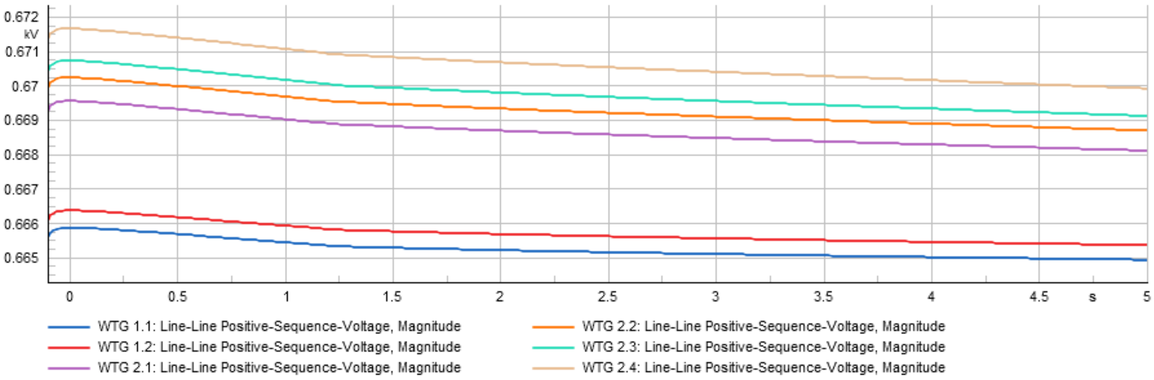


Figure 5.32: **Voltage with 15MW with load BESS**

The comparison of Figures 5.30 and 5.31 demonstrates the critical role of BESS in maintaining frequency stability during load variations. Without BESS, the frequency drop is more severe and prolonged, posing a threat to grid reliability. With BESS, the frequency is more stable, with fewer dips and faster recovery, demonstrating its ability to handle sudden load increases effectively. This is consistent with the findings of Bokde et al. (2018), which discuss the need for advanced control strategies, including storage, to mitigate the frequency deviations caused by load and generation mismatches.

5.4.4. Active Power

When a 15 MW load is added to the PCC with BESS in service, as assumed in Figure 5.34, the active power output at the WTGs remains relatively stable. BESS compensates for the increased load by supplying additional active power, reducing the burden on the WTGs, and preventing significant disruptions in their output. This stabilising effect is supported by Li et al. (2016), who note that BESS can rapidly inject power to balance load variations, maintaining a consistent active power flow in renewable systems. BESS ensures that the WTGs continue operating within their optimal range, avoiding sharp drops or fluctuations, as highlighted by de Siqueira and Peng (2021), who discuss how BESS smooths power output during load changes. The active power profile in Figure 5.34 shows minimal deviation, demonstrating BESS's ability to manage the load increase effectively.

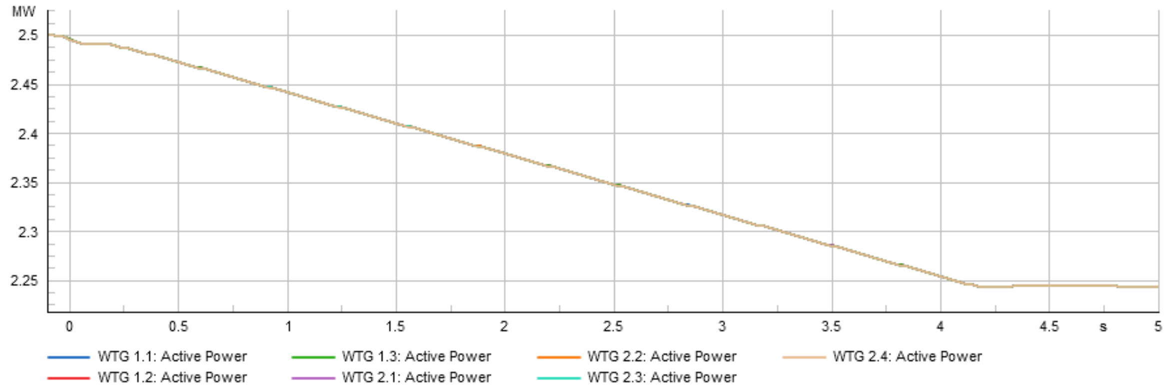


Figure 5.33: Active power with 15MW without load BESS

Without a battery energy storage system, as shown in Figure 5.35, the active power output at the WTGs is significantly affected when the 15 MW load is added. The sudden increase in demand creates a power imbalance, forcing the WTGs to attempt to supply more power. This can lead to a drop in active power output if the turbines reach capacity limits or controllers throttle output to maintain stability. This is consistent with Datta et al. (2019), who explain that load increases in wind-integrated systems without storage can cause power mismatches, thereby leading to instability or reduced output. Attya et al. (2018) further note that the wind farms struggle to respond to load variations without fast-acting support, thus resulting in potential power drops or system stress. The active power profile in Figure 5.35 likely shows a noticeable dip or fluctuation, reflecting the system's inability to compensate for the load without BESS fully.

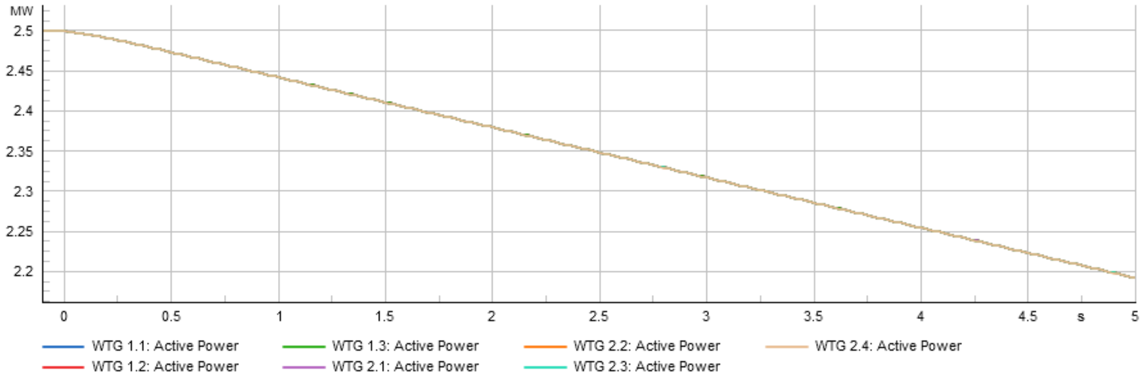


Figure 5.34: Active power with 15MW load without BESS

Assuming Figure 5.34 represents the scenario with BESS, the comparison with Figure 5.35 highlights the critical role of BESS in maintaining active power stability. Without BESS, the active power output suffers from significant drops or fluctuations due to the load increase, risking grid reliability. With BESS, the power output remains more consistent as the storage system buffers the demand, ensuring smoother operation of the WTGs. This aligns with Yang et al. (2018), who emphasise the importance of energy storage in managing power variations in renewable systems, and Ourahou et al. (2020), who advocate for storage to enhance grid resilience during load changes.

5.4.5. Reactive Power

When a 15 MW load is added to the PCC without BESS as shown in Figure 5.36, the reactive power at the wind turbine generators is significantly affected. The sudden load increase creates a demand for additional reactive power to maintain voltage stability, which the WTGs struggle to supply without external support. This can lead to reactive power fluctuations or absorption (negative MVAr), as the turbines adjust to balance the system, potentially compromising power quality. Kumar et al. (2014) note that the wind turbines may absorb reactive power during load changes to stabilise local voltages, but this can lead to instability without storage. Liang (2016) further explains that the renewable-integrated grids face reactive power challenges during load variations, resulting in erratic profiles that risk voltage deviations. The reactive power in Figure 5.36 shows pronounced swings or increased absorption, indicating the system's struggle to cope with the load.

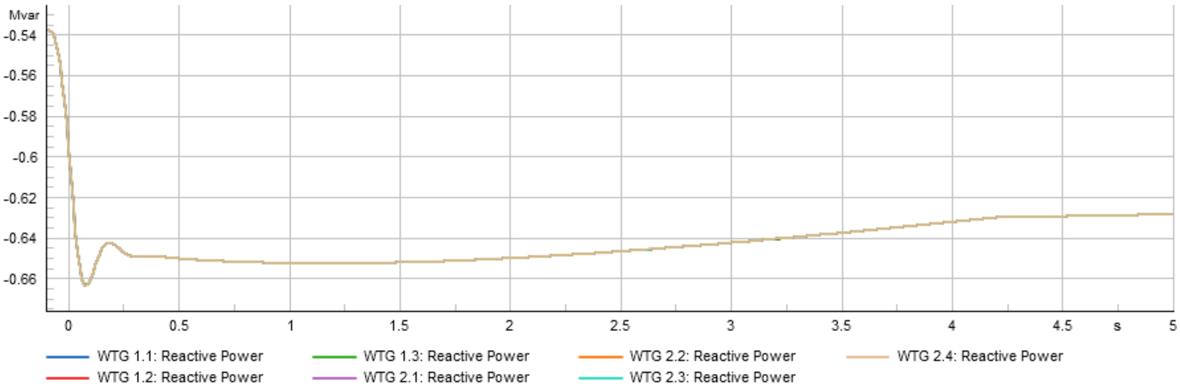


Figure 5.35: **Reactive power with 15MW load without BESS**

With a BESS in service, as depicted in Figure 5.37, the reactive power behaviour improves significantly when the 15 MW load is added. The BESS supports the system by supplying or absorbing reactive power as needed, stabilising voltage and reducing the burden on the WTGs. This results in a smoother reactive power profile with fewer fluctuations or excessive absorption. Stecca et al. (2020) highlight that BESS can enhance the reactive power control in wind farms by coordinating with turbines to maintain power quality during dynamic events like load changes. Similarly, Khalid et al. (2021) note that BESS integration optimises reactive power management, ensuring compliance with grid requirements. The reactive power in Figure 5.37 likely shows a more stable output, with BESS mitigating the impact of the load increase, as supported by Gomez et al. (2020), who emphasise BESS's role in improving power quality in wind-integrated systems.

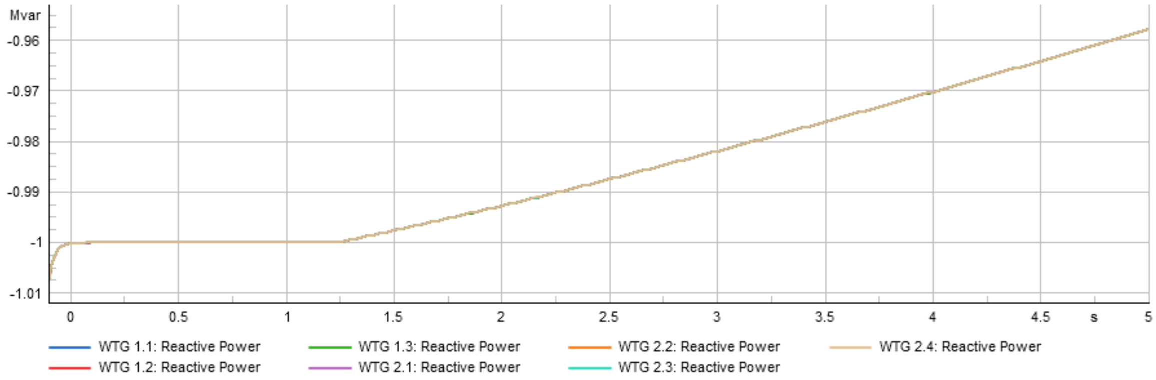


Figure 5.36: Reactive power with 15MW load with BESS

The comparison between Figures 5.36 and 5.37 underscores the critical role of BESS in managing reactive power during load variations. Reactive power exhibits significant fluctuations or absorption without BESS, risking voltage instability and poor power quality. With BESS, the reactive power profile is more stable, demonstrating its ability to support the WTGs and maintain system balance. This aligns with Ourahou et al. (2020), who advocate for energy storage to enhance grid reliability under varying loads, and Yang et al. (2018), who highlight storage's importance in mitigating power variations in renewable systems.

5.4.6. Three phase Current

When a 15 MW load is added to the PCC without BESS, as shown in Figure 5.38, the current at the WTGs or network nodes increases significantly. The sudden load demand forces the WTGs to supply more power, resulting in a spike in current as the system attempts to meet the new requirement. Without BESS, there is no mechanism to buffer this demand, leading to potential overcurrent conditions that stress the turbines and network components. This is supported by Abbas and Chowdhury (2021), who note that load increases in renewable-integrated grids can cause excessive current flows without storage, risking equipment damage or instability. Liang (2016) further explains that such systems are prone to current surges during load variations, as the WTGs alone struggle to balance the power flow, potentially leading to voltage drops or protection triggers. The current profile in Figure 5.38 likely shows a sharp increase with possible fluctuations, reflecting the system's strain.

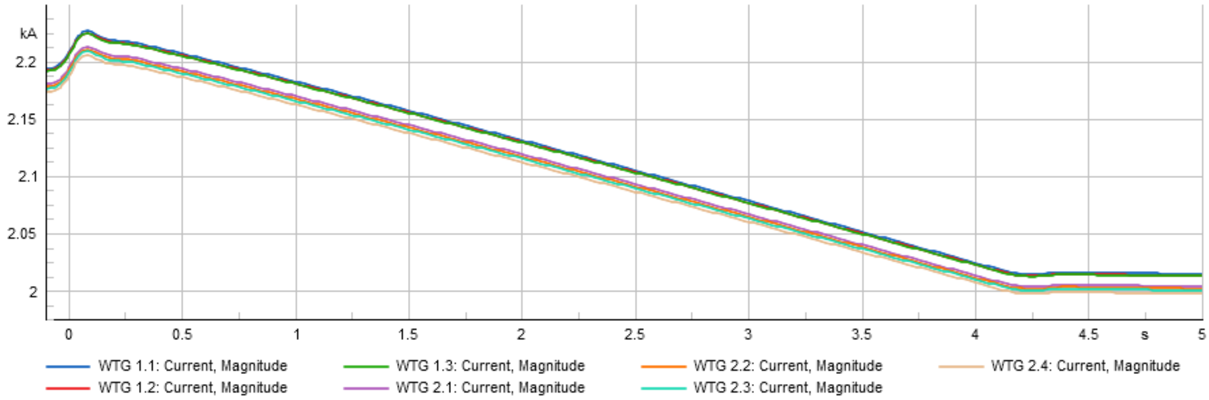


Figure 5.37: **Current with 15MW without load BESS**

With a BESS in service, as depicted in Figure 5.39, the current response to the 15 MW load addition is more controlled. The BESS supplies additional active power to meet the load demand, reducing the current drawn from the WTGs and mitigating spikes. This results in a smoother current profile with lower peaks, as the BESS acts as a buffer to stabilise power flow. Stecca et al. (2020) highlight that BESS integration can manage current surges by providing rapid power adjustments, protecting the network from overloading during load changes. Similarly, Li et al. (2016) note that BESS helps to maintain stable current levels by balancing load variations and enhancing overall system reliability. The current in Figure 5.39 likely shows a moderated increase compared to Figure 5.38, demonstrating the BESS's effectiveness in preventing excessive current stress.

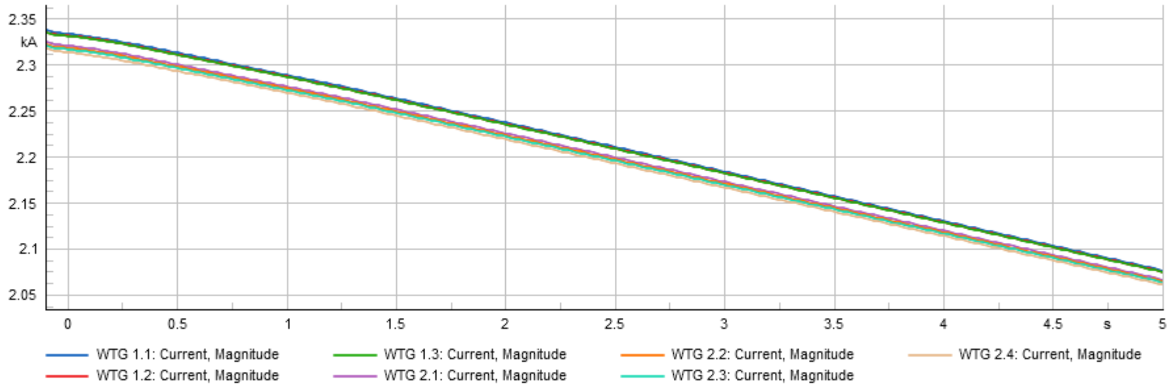


Figure 5.38: **Current with 15MW load with BESS**

The comparison between Figures 5.38 and 5.39 underscores the critical role of BESS in managing current during load variations. Without BESS, the current spikes significantly, posing equipment and grid stability risks. With BESS, the current increase is tempered, with smoother behaviour and reduced stress on the WTGs, highlighting its importance in maintaining reliable operation. This aligns with Ourahou et al. (2020), who emphasise the role of energy storage in enhancing grid resilience under dynamic loads, and Yang et al. (2018), who stress its ability to mitigate power flow variations in renewable systems.

5.5. Wind Turbine Analysis

5.5.1. Load Flow

Figure 5.39 shows the voltage profile at the PoC/PCC under normal network conditions. Without BESS, the voltage exhibits fluctuations due to the intermittent nature of wind power, as mismatches between generation and load cause instability (Abbas & Chowdhury, 2021). With BESS, the voltage is more stable, as the storage system absorbs or supplies power to mitigate rapid changes in active power output, enhancing voltage regulation (Abdelrahman et al., 2022). The BESS buffers the variability of WTG1's output, ensuring a consistent voltage profile, which is critical for grid reliability in renewable-dominated systems (Yang et al., 2018).

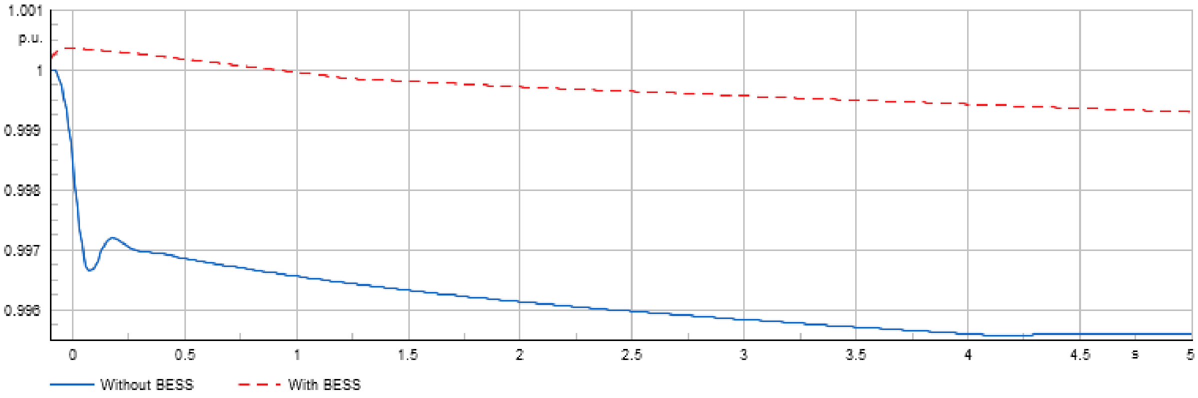


Figure 5.39: **PoC/PCC Voltage Profile, With and Without BESS (No fault)**

Figure 40 plots the frequency at WTG1, scaled between 49.998 Hz and 50.005 Hz, under normal conditions. Without BESS, frequency fluctuations are more pronounced due to the stochastic wind power output, as WTG1 lacks a fast-response mechanism to balance generation and load (Datta et al., 2019). With BESS, frequency stability improves, as the storage system rapidly adjusts power to smooth oscillations, maintaining frequency closer to the nominal 50 Hz (Li et al., 2016). The BESS's ability to provide quick power adjustments reduces deviations, ensuring stable operation for WTG1 (de Siqueira & Peng, 2021).

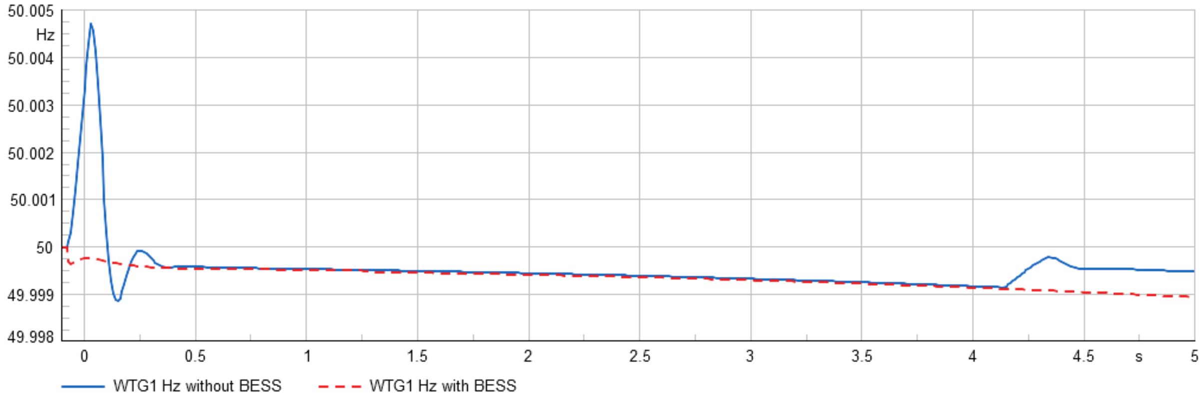


Figure 5.40: **System Frequency at WTG1**

Figure 5.41 illustrates the voltage at WTG1 under normal conditions. Without BESS, WTG1 experiences significant voltage variations driven by intermittent wind generation, leading to potential drops or spikes (Mostafa et al., 2022). The absence of storage exacerbates these fluctuations, as WTG1 relies on turbine controllers alone (Abbas & Chowdhury, 2021). With BESS, the voltage profile is smoother, as the storage system regulates power flow to stabilize voltage, reducing deviations and improving power quality (Abdelrahman et al., 2022). This highlights BESS's role in mitigating WTG1's voltage instability.

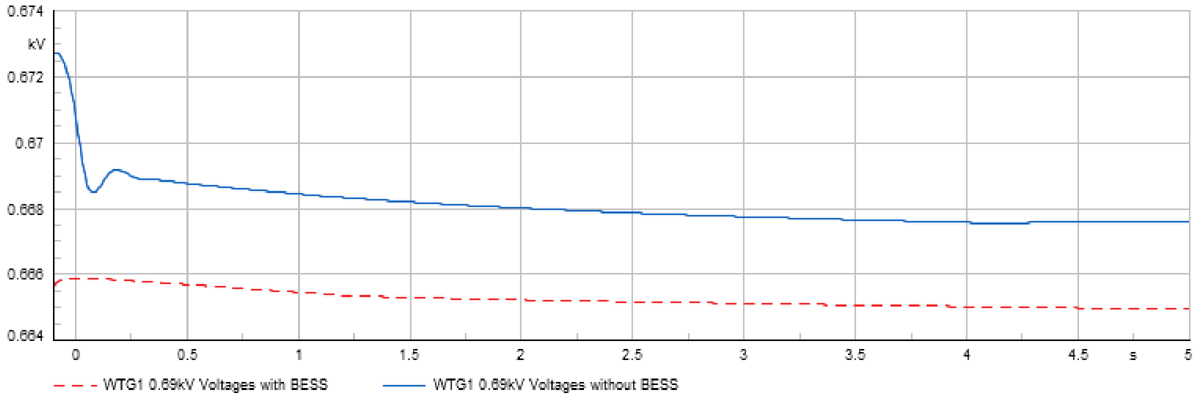


Figure 5.41: **Voltage at WTG1**

Figure 5.42 shows the active power output at WTG1. Without BESS, a slight drop in output is observed, likely due to the turbine controller throttling power to prevent exceeding the Maximum Export Capacity (MEC) or to correct a slightly high frequency (Attya et al., 2018). With BESS, WTG1's output is throttled further, as the storage system manages power flow to maintain system balance, reducing WTG1's output to avoid overproduction (Li et al., 2016). The BESS optimizes dispatch, allowing WTG1 to operate at a lower, stable output, enhancing grid stability (de Siqueira & Peng, 2021).

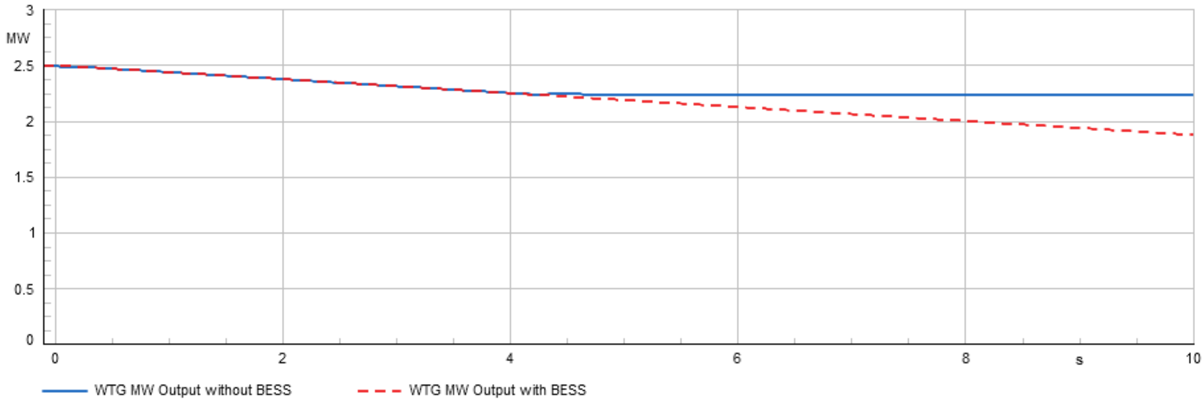


Figure 5.42: **Active power at WTG1**

Extending the timeframe of Figure 5.43 to 50 seconds, this figure shows the stabilization of WTG1's active power output. Without BESS, the output stabilizes after initial throttling but remains susceptible to fluctuations due to wind variability. With BESS, WTG1 stabilizes at a significantly reduced output (e.g., ~1 MW), as the BESS absorbs excess power to prevent frequency or MEC issues (Li et al., 2016). This controlled reduction demonstrates BESS's ability to fine-tune WTG1's output for long-term stability (Yang et al., 2018).

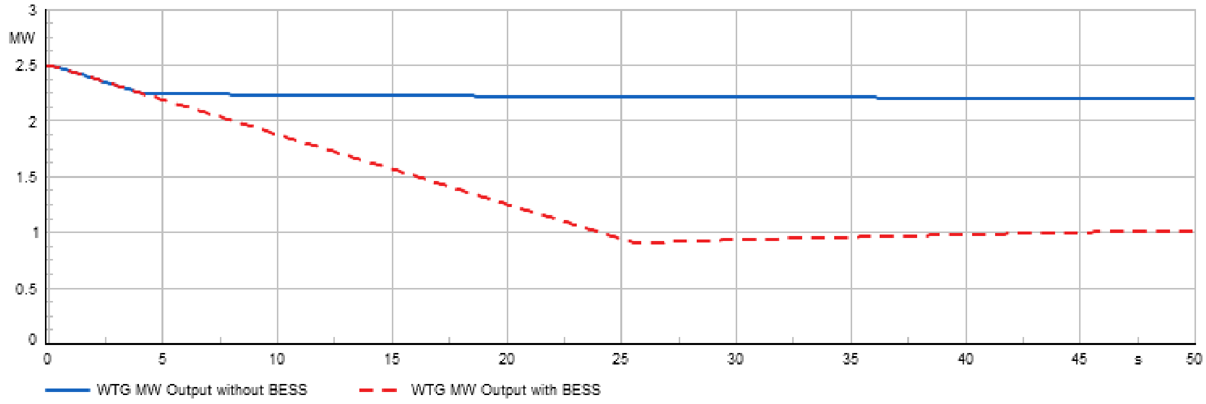


Figure 5.43: **Active power at WTG1**

Figure 5.44 depicts WTG1's reactive power, which is negative (indicating absorption, in MVAr) in both scenarios. Without BESS, WTG1 absorbs reactive power to support its operation or maintain voltage stability, as is typical in wind turbines with power electronics (Kumar et al., 2014). With BESS, absorption increases, suggesting that BESS alters WTG1's operating mode, possibly by adjusting the power factor or voltage profile at the PoC (Stecca et al., 2020). The BESS's influence allows WTG1 to operate in a controlled manner, potentially to prevent overvoltage, but increases reactive power demand (Khalid et al., 2021).

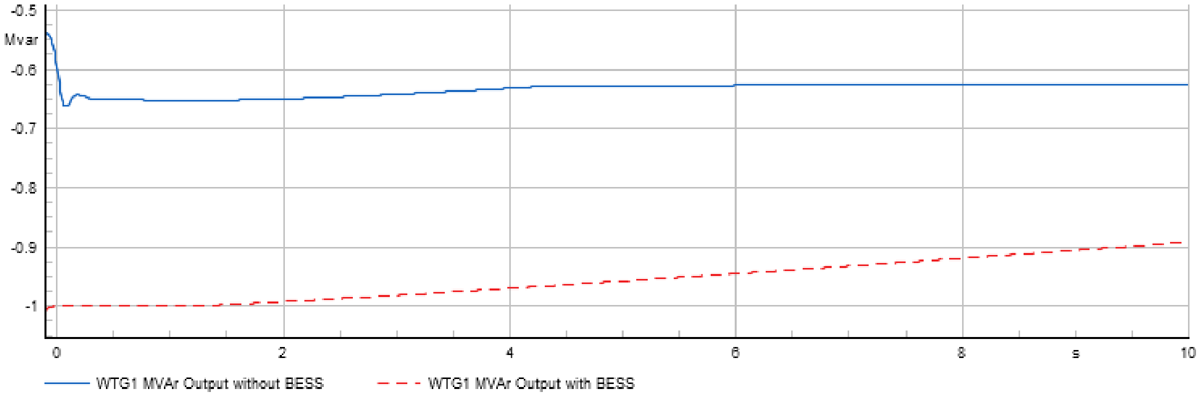
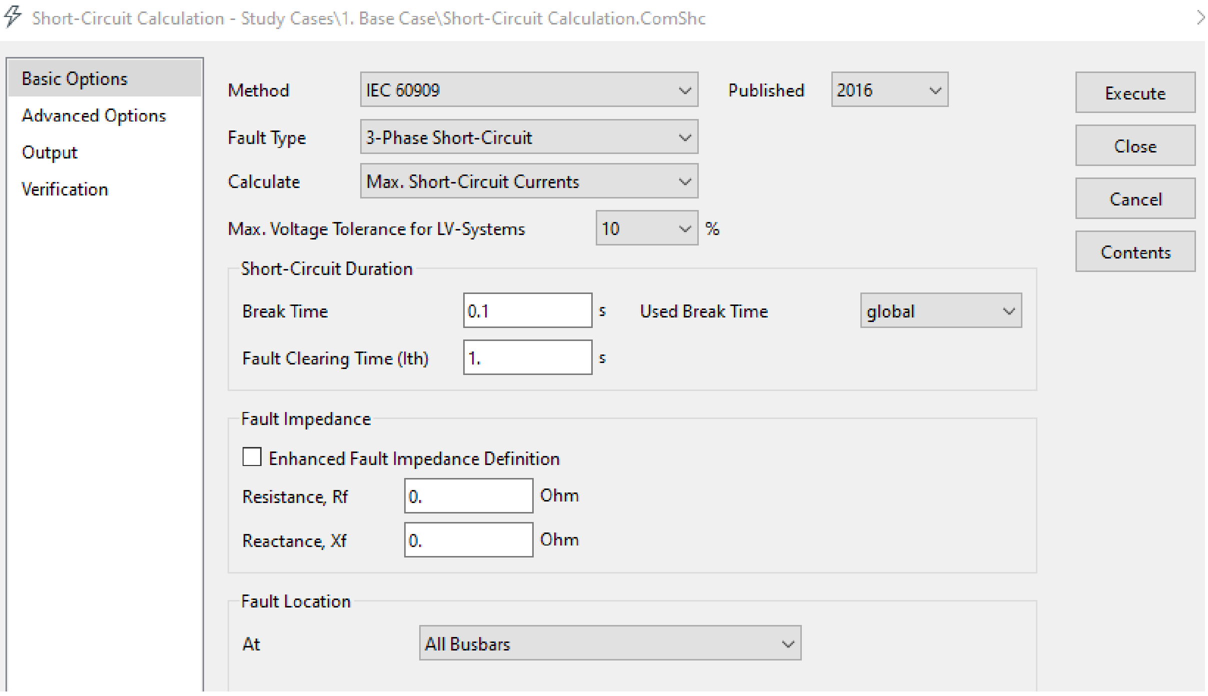


Figure 5.44: **Reactive Power at WTG1**

5.5.2. Fault Analysis

This figure 5.45 and 5.46 outlines the fault calculation settings in DIgSILENT PowerFactory for the three-phase short circuit on cable 2.1. It specifies parameters such as fault type, location, and impedance, which are critical for accurate quasi-dynamic simulation (DIgSILENT, 2021).

These settings ensure the fault's impact on WTG1 and the network is modelled realistically, accounting for current distribution and system response.



Short-Circuit Calculation - Study Cases\1. Base Case\Short-Circuit Calculation.ComShc

Method IEC 60909

Published 2016

Fault Type 3-Phase Short-Circuit

Calculate Max. Short-Circuit Currents

Max. Voltage Tolerance for LV-Systems 10 %

Short-Circuit Duration

Break Time 0.1 s

Used Break Time global

Fault Clearing Time (Ith) 1. s

Fault Impedance

☐ Enhanced Fault Impedance Definition

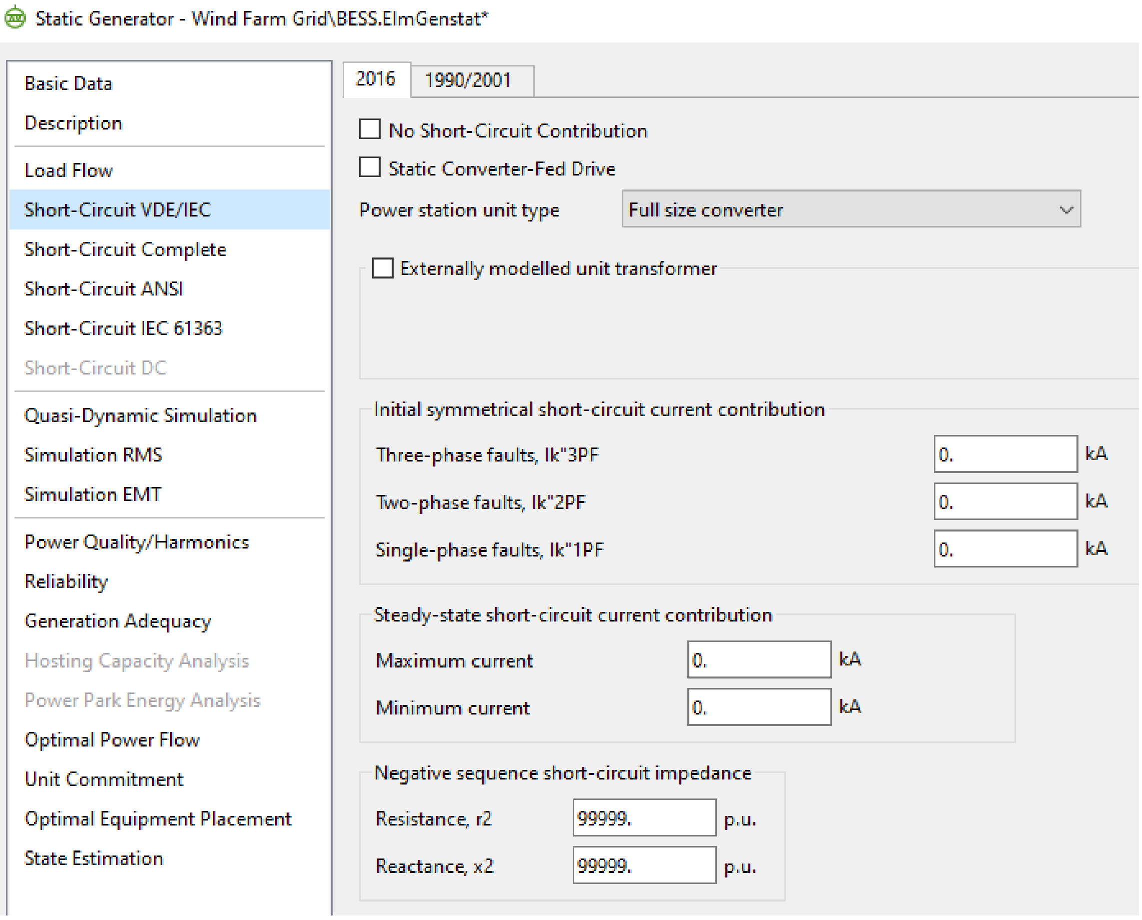
Resistance, Rf 0. Ohm

Reactance, Xf 0. Ohm

Fault Location

At All Busbars

Figure 5.45: Fault Parameters Settings



Static Generator - Wind Farm Grid\BESS.ElmGenstat*

☐ No Short-Circuit Contribution

☐ Static Converter-Fed Drive

Power station unit type Full size converter

☐ Externally modelled unit transformer

Initial symmetrical short-circuit current contribution

Three-phase faults, Ik"3PF 0. kA

Two-phase faults, Ik"2PF 0. kA

Single-phase faults, Ik"1PF 0. kA

Steady-state short-circuit current contribution

Maximum current 0. kA

Minimum current 0. kA

Negative sequence short-circuit impedance

Resistance, r2 99999. p.u.

Reactance, x2 99999. p.u.

Figure 5.46: Fault Calculation Settings

Figure 5.47 illustrates the network configuration during the fault, showing cable 2.1’s midpoint fault location. It highlights how the fault divides the network, potentially isolating turbines on the “2” side (downstream) while WTG1, assumed on the “1” side (grid-connected), remains partially supported by the grid. This configuration influences WTG1’s voltage, frequency, and power responses (DIgSILENT, 2021).

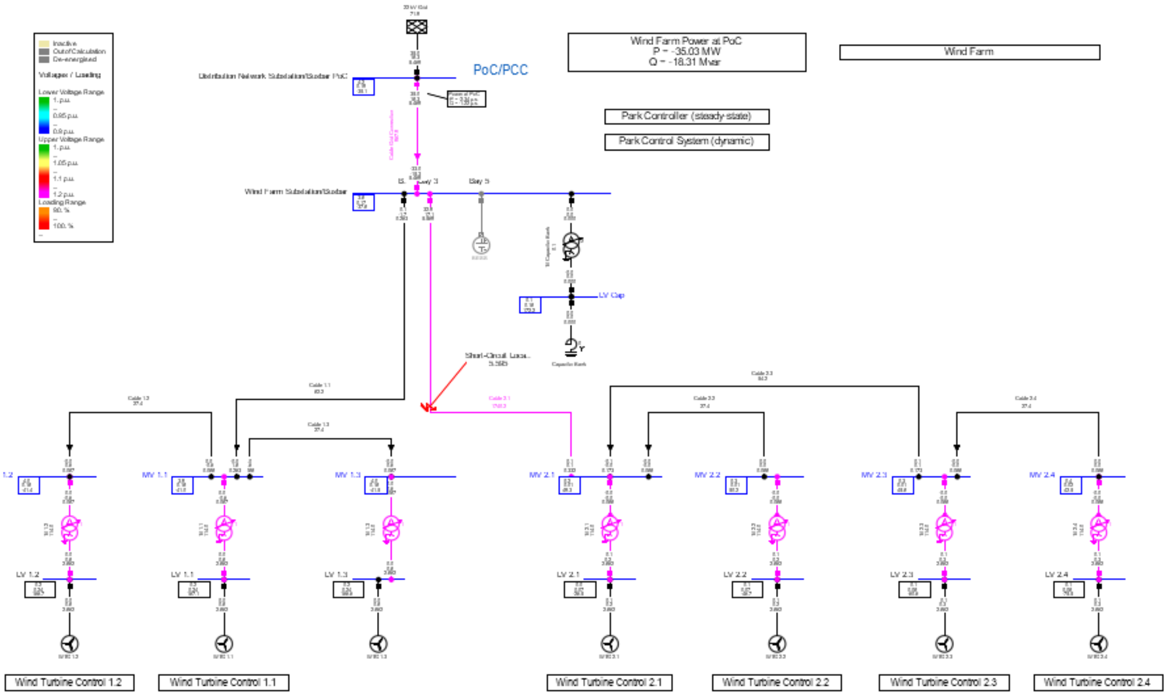


Figure 5.47: **Network representation of a 3-phase short circuit occurs on cable 2.1**

Figure 5.48 shows the PoC/PCC voltage during the fault. Without BESS, the voltage drops severely due to high fault currents, collapsing to a low residual value (DIgSILENT, 2021). With BESS, the voltage remains low (4 kV, 18% of nominal), limiting BESS’s active power output to 1.4 MW (18% capacity). The BESS mitigates the drop slightly by injecting power, but the fault’s severity constrains its effectiveness (Stecca et al., 2020). This indicates WTG1’s operation is heavily impacted, even with BESS support (Abdelrahman et al., 2022).

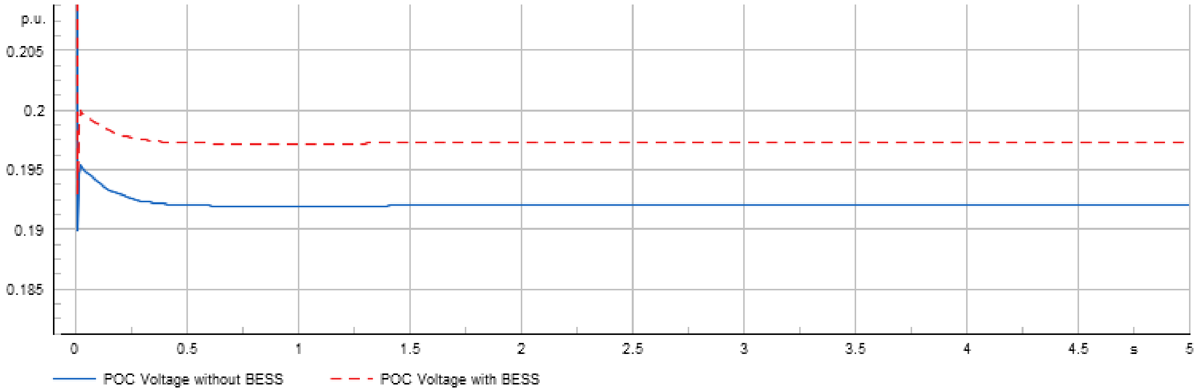


Figure 5.48: **POC Voltage when there is a 3-phase fault on cable 2.1**

Figure 5.49 plots WTG1's frequency during the fault. Without BESS, the frequency dips significantly as the fault disrupts power flow, with WTG1 (on the "1" side) experiencing a less severe drop due to grid connection (Datta et al., 2019). The dip is reduced with BESS, as the storage system injects power to stabilise frequency, aiding quicker recovery (Li et al., 2016). The BESS's rapid response mitigates WTG1's frequency instability, though complete stabilisation is limited by the fault's magnitude (de Siqueira & Peng, 2021).

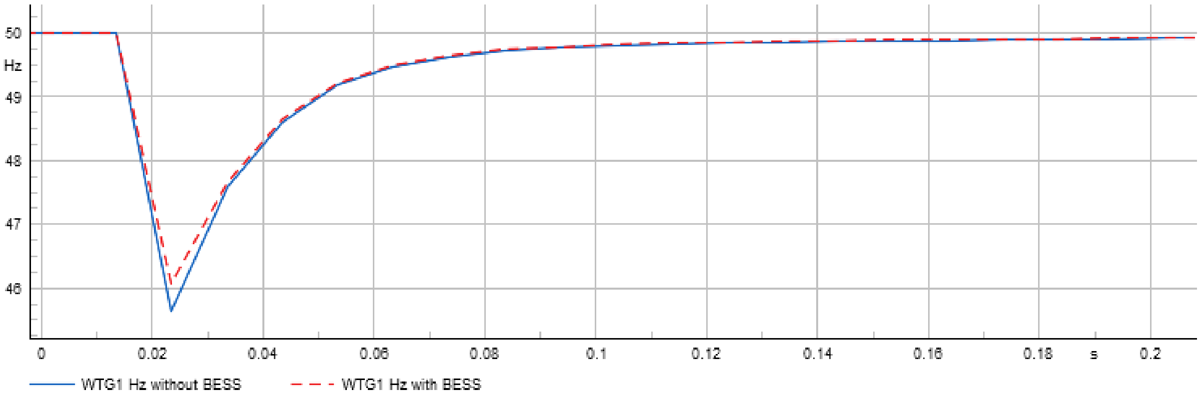


Figure 5.49: Frequency at WTG1 3-phase fault on cable 2.1

Figure 5.50 shows WTG1's voltage during the fault. Without BESS, the voltage collapses due to the fault's high current and disrupted flow, reflecting WTG1's vulnerability without storage (Mills et al., 2020). With BESS, the voltage drop is less severe, as the storage system supports voltage regulation, but remains low due to the fault's impact (Stecca et al., 2020). This demonstrates BESS's limited but beneficial role in enhancing WTG1's fault ride-through capability (Abdelrahman et al., 2022).

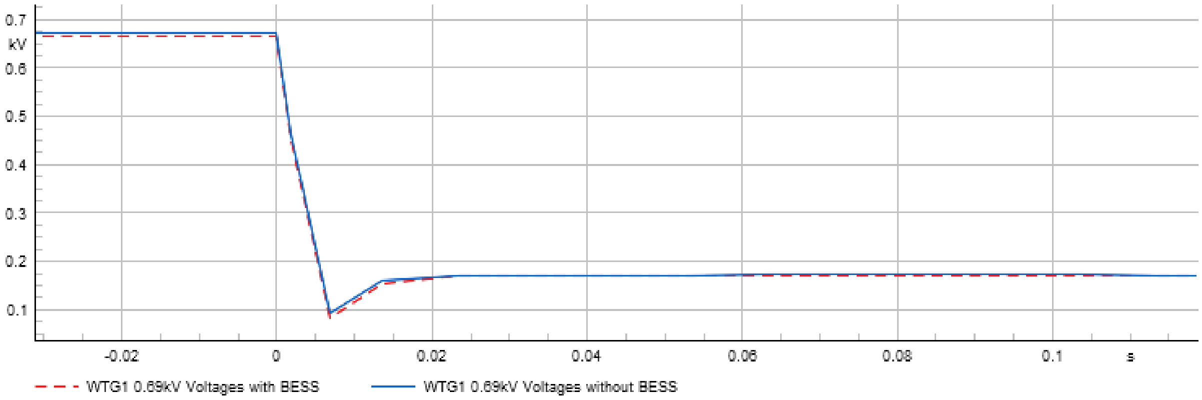


Figure 5.50: Voltage at WTG1 3-phase fault on cable 2.1

Figure 51 depicts active power without BESS; WTG1's active power drops significantly as the fault disrupts generation, with partial grid support (on the "1" side) mitigating the impact slightly (Datta et al., 2019). The drop is less severe with BESS, as the storage system injects power to stabilise output, aiding recovery (Li et al., 2016).

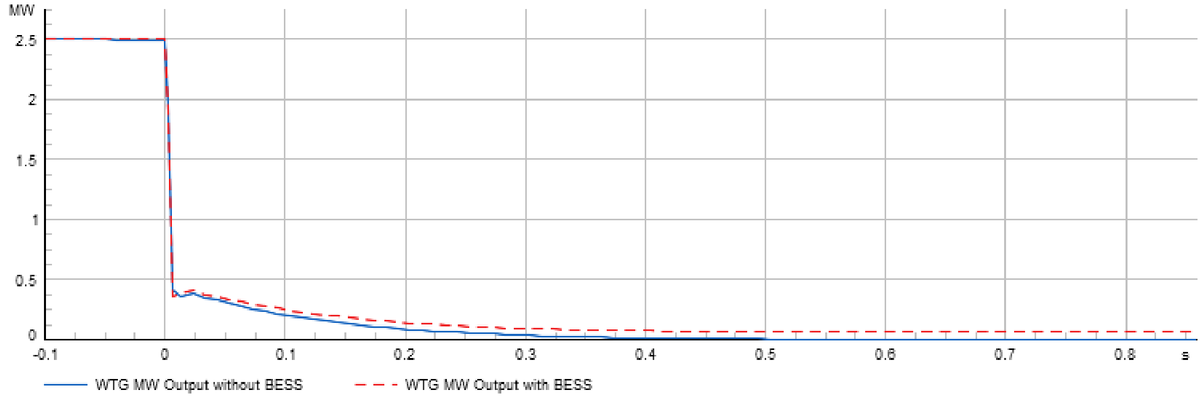


Figure 5.51: Active Power at WTG1 3-phase fault on cable 2.1

Figure 5.52 depicts that WTG1 absorbs more reactive power to maintain local voltage without BESS, exacerbating instability (Kumar et al., 2014). With BESS, reactive power fluctuations are reduced, as the storage system supports voltage stability, minimising absorption (Stecca et al., 2020). This shows BESS's role in stabilising WTG1's power output during faults.

Figure 5.53 shows WTG1's current during the fault. Without BESS, a significant current surge occurs due to the low-impedance fault path, stressing WTG1 and network components (Mills et al., 2020). BESS reduces the surge, as the storage system absorbs or injects power to limit current spikes, protecting WTG1 (Stecca et al., 2020). The BESS's buffering effect enhances WTG1's resilience, though some surge persists due to the fault's severity (Abdelrahman et al., 2022).

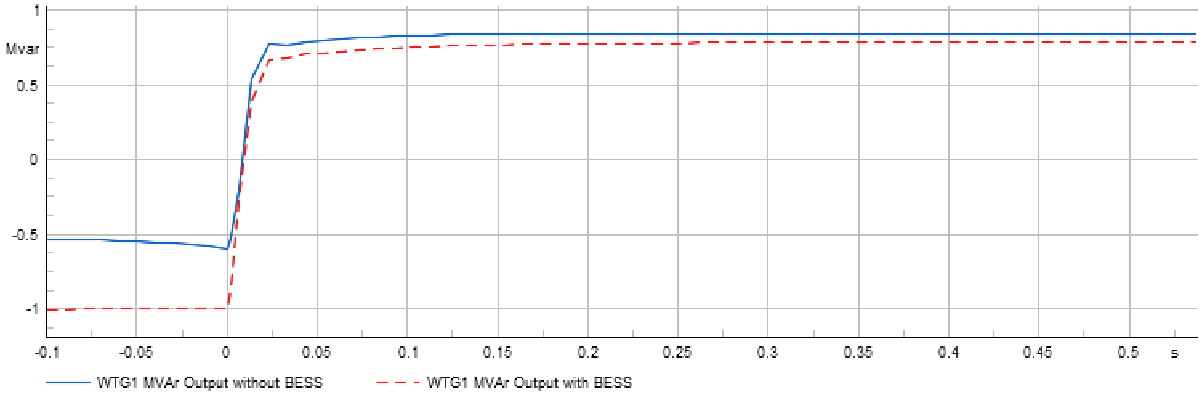


Figure 5.52: Reactive Power at WTG1 3-phase fault on cable 2.1

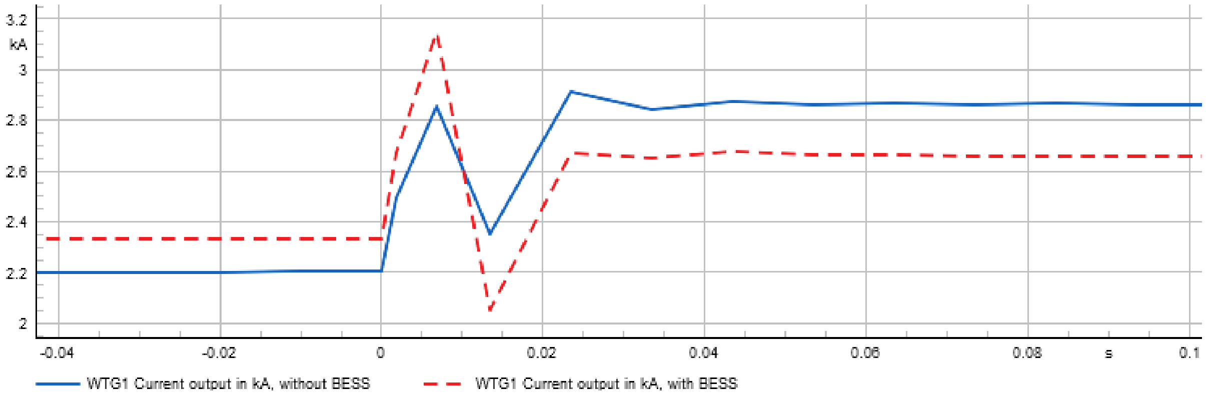


Figure 5.53: **Current at WTG1 3-phase fault on cable 2.1**

5.5.3. Load Studies

Figure 5.54 shows the PoC/PCC voltage when a 15 MW load is added. Without BESS, the voltage drops noticeably due to the power imbalance caused by increased demand, as WTG1 struggles to compensate (Abbas & Chowdhury, 2021). With BESS, the voltage remains more stable, as the storage system supplies active power to mitigate the drop, enhancing regulation (Li et al., 2016). The BESS's rapid response ensures WTG1 operates under stable conditions (Abdelrahman et al., 2022).

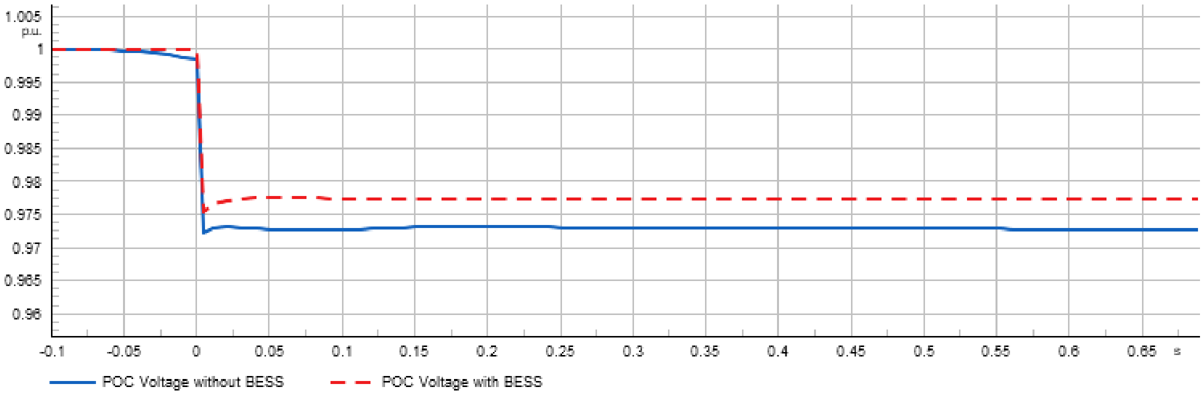


Figure 5.54: **POC Voltage when 15MW load is added**

Figure 5.55 plots WTG1's frequency during the load increase. Without BESS, the frequency dips significantly, as the sudden load outstrips WTG1's generation capacity, relying on slow grid support (Datta et al., 2019). The dip is minimised with BESS, as the storage system injects power to balance the load, ensuring faster frequency recovery (Li et al., 2016). The BESS's role in mimicking inertia stabilises WTG1's frequency (de Siqueira & Peng, 2021).

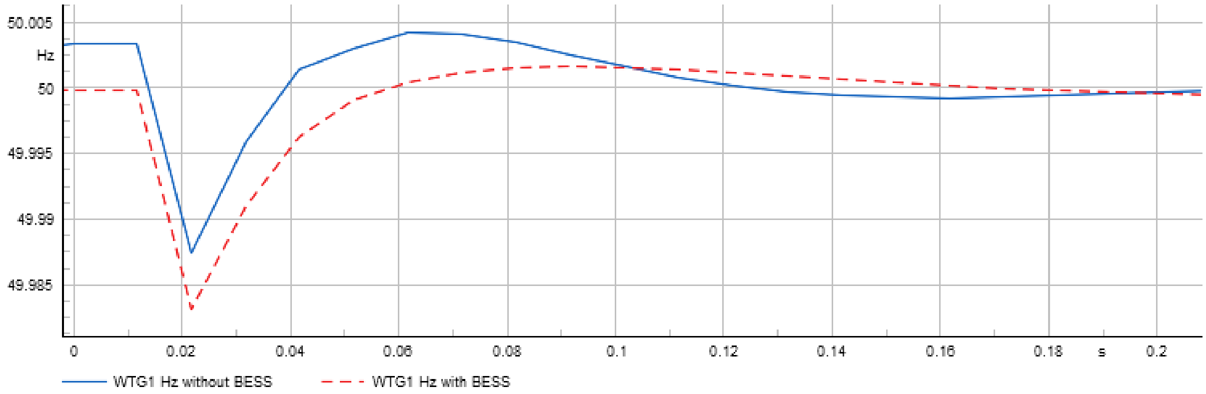


Figure 5.55: Frequency when a 15MW load is added

Figure 5.56 shows WTG1's voltage during the load increase. Without BESS, the voltage drops due to the increased demand, reflecting WTG1's limited ability to maintain stability without storage (Abbas & Chowdhury, 2021). With BESS, the voltage is more stable, as the storage system regulates power flow to prevent significant sags, supporting WTG1's operation (Abdelrahman et al., 2022). The BESS's voltage regulation enhances WTG1's reliability under load stress.

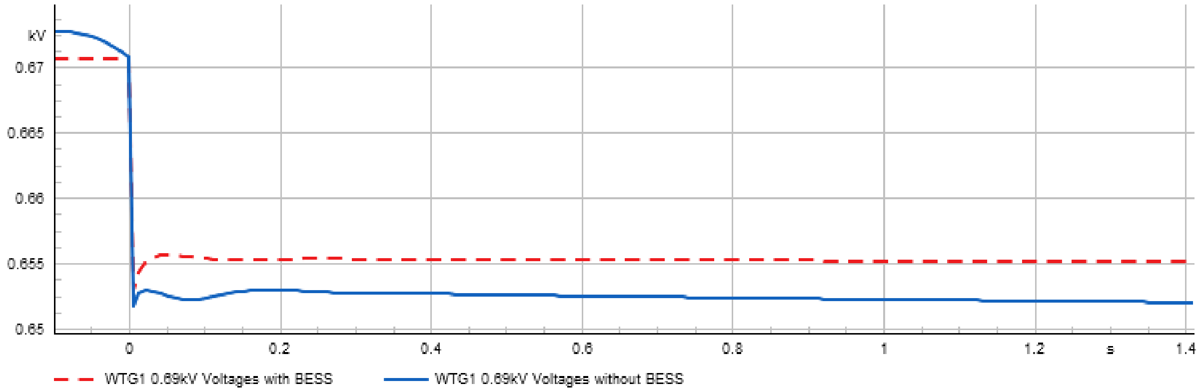


Figure 5.56: Voltage when a 15MW load is added

Figure 5.57 depicts that WTG1's active power without BESS drops or fluctuates as it attempts to meet the 15 MW load, risking instability if capacity limits are reached (Datta et al., 2019). With BESS, WTG1's output remains stable, as the storage system supplies additional power, reducing stress on the turbine (Li et al., 2016). The BESS ensures WTG1 operates smoothly, avoiding significant disruptions (de Siqueira & Peng, 2021).

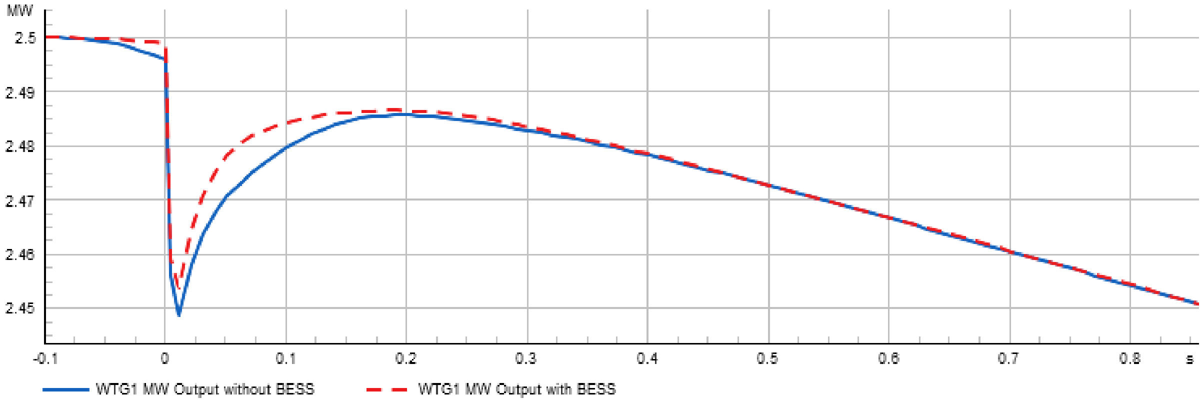


Figure 5.57: Active Power when a 15MW load is added

Figure 5.58 shows that WTG1 absorbs more reactive power (negative MVAr) to stabilise voltage without BESS, leading to fluctuations and potential instability (Kumar et al., 2014). With BESS, reactive power is more stable, as the storage system supplies or absorbs MVAr to support voltage, reducing WTG1's absorption (Stecca et al., 2020). The BESS's coordination enhances WTG1's power quality (Khalid et al., 2021).

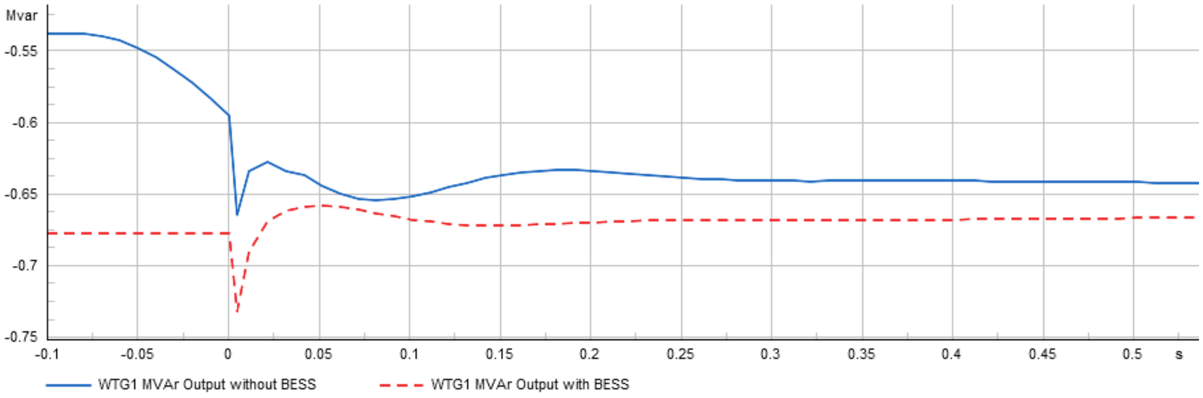


Figure 5.58: Reactive Power when a 15MW load is added

5.6. Discussion of Results

The quasi-dynamic simulations conducted at the Chaba Wind Farm provide compelling evidence of the effectiveness of integrating a BESS to address the research aim of mitigating wind power variability, enhancing grid stability, and maximising reliability and sustainability in South Africa's power grid. The results directly align with the four research objectives. First, the significant voltage, frequency, and active power fluctuations observed without BESS (Figures 5.1, 5.3, 5.5, 5.7) confirm the challenges of renewable energy variability, as noted by Abbas and Chowdhury (2021) and Mostafa et al. (2022), highlighting the grid's vulnerability to power imbalances in South Africa's context. With BESS, these parameters stabilise significantly (Figures 5.2, 5.4, 5.6, 5.8, 5.9), reducing fluctuations and improving power quality, as supported by Li et al. (2016) and Yang et al. (2018). However, the unexpected increase in reactive power absorption with BESS (Figures 5.11, 5.27, 5.37) suggests that control strategies may prioritise active power, requiring WTGs to compensate for voltage regulation, a finding that deviates from Khalid et al. (2021) and warrants further investigation.

The fault analysis results demonstrate BESS's role in enhancing Fault Ride-Through (FRT) capabilities, partially fulfilling the third objective, though limitations persist. Without BESS, severe voltage drops, frequency dips, and current surges occur during a three-phase fault on cable 2.1 (Figures 5.15, 5.19, 5.22), particularly affecting islanded “2” side turbines, as noted by Datta et al. (2019). With BESS, these impacts are mitigated (Figures 5.16, 5.21, 5.23), but the residual voltage of only 4 kV (18% of nominal) indicates that fault severity and BESS capacity constraints limit full stabilisation, partially contradicting Abdelrahman et al. (2022). Load studies further support the fourth objective of scalability, showing that BESS stabilises voltage, frequency, and power outputs when a 15 MW load is added (Figures 5.29, 5.31, 5.34, 5.37, 5.39), aligning with Ourahou et al. (2020). The persistent reactive power absorption under load conditions suggests scalability may require site-specific control adjustments, as Gomez et al. (2020) support.

These results are significant for South Africa's renewable energy goals, as they demonstrate BESS's ability to enhance grid reliability and power quality, reducing risks like load shedding and equipment stress. The findings align with prior studies but highlight areas for improvement, such as optimising reactive power management and increasing BESS capacity for severe faults. The increased reactive power absorption may result from control settings prioritising active power, while limited fault recovery likely stems from fault severity and network isolation, as noted by DIgSILENT (2021). These insights provide a foundation for refining BESS-integrated wind farm designs, ensuring adaptability to broader renewable energy systems and contributing to a sustainable, reliable power grid in South Africa.

5.7. Summary

Chapter 5 illustrated that the incorporation of BESS markedly enhances the performance, stability, and reliability of a 21 MW wind farm, especially at the wind farm and individual wind turbine (WTG1) levels, as evidenced by quasi-dynamic simulations in DIgSILENT PowerFactory. BESS effectively stabilises voltage, frequency, active and reactive power under normal load flow conditions, mitigates significant disturbances during three-phase faults, and ensures operational continuity during load increases, such as the addition of a 15 MW demand, by minimising voltage and frequency dips and regulating current surges. BESS integration facilitates more efficient operational profiles and expedited recovery, underscoring its critical function in improving wind-integrated renewable energy systems' dynamic responsiveness and grid compatibility.

CHAPTER SIX

CONCLUSION AND FUTURE WORK

6.1. Introduction

This chapter consolidates the research outcomes on integrating BESS with wind farms, focusing on their potential to mitigate power generation variability and enhance grid stability. The study's findings, implications, and recommendations are summarised to provide actionable insights for stakeholders, including policymakers, energy industry practitioners, and researchers. The chapter also outlines areas where further investigation is needed to advance the scalability and efficiency of wind-BESS hybrid systems. By addressing the achievements and limitations of this research, this chapter provides a comprehensive conclusion and a forward-looking perspective to guide future work in renewable energy integration.

This chapter seeks to conclude the findings from the simulations and work done for the integration of the BESS to a Wind Farm with the purpose of mitigating power variations fed to the grid. The study has been broad enough to show the need for this technology, highlighting the positive improvement after the integration, which includes power output stability, frequency response, and fault recovery speed. The study also showed that the deployment of this technology is a need and a must, considering environmental factors around the technology itself, climate prediction accuracy is an issue and was overcome by the employment of this integration.

6.2. Summary of Key Findings

The research effectively met the aim of developing a wind farm integrated with BESS to reduce wind power generation variability and improve grid stability. The following are the main conclusions that support the goals of the study:
Globally, technology investors have delved into this type of solution to the industry, harvesting maximum power for the consumers and making sure that grid issues are addressed at peak demands. On this note the following achievements were:

i. Stabilising power variations

Consumers' needs differ during the day and at night, this has a significant effect on the grid frequency issues. This integration has dealt with one of the major issues of grid power variations. Response time improvement to changes experienced by the grid was properly addressed.

ii. Enhanced Fault Ride-Through (FRT) capabilities

The fault ride-through capability of wind turbines based on Double Fed Induction Generators (DFIG) that are susceptible to grid disruptions is enhanced by BESS. The system prevents outages and ensures continuous energy delivery by maintaining operational stability during grid faults.

The integration showed efficient endurance behaviour during Voltage sags and other grid issues, which the system efficiently sustained during those terms. Continuous power supply was maintained and archived. With a correct BESS sizing, the integration overperformed. To achieve the enhanced fault ride-through capabilities requires a robust system in place to address any possible grid issues that might be experienced; in this case, BESS addressed the issue efficiently.

iii. Scalability and applicability

The model provides a flexible solution for various operational and geographic situations since it is scalable and adjustable to different wind farms. The results imply that other renewable energy projects can imitate wind farms and BESS integration to improve grid dependability and further sustainability objectives.

The application of this technology is possible anywhere within the utility scale, while it was chosen for a selected wind farm. In this case, it ensured that the system could handle an increasing workload and significant grid changes, and it was proven to be applicable and capable. The system was considered suitable and intended for the technology.

iv. Grid stability and compliance

The study and simulations have assured the system’s reliability, efficiency, safety and consistency with the intended technical application. Grid code compliance is possible, and related issues were addressed. The system can withstand faults and respond timeously while maintaining the acceptable voltage level and frequencies. It provides sufficient grid support, prevents grid outages and ensures a stable power supply.

v. Performance under varying conditions

The system functions well in various operational situations, such as seasonal changes in wind speed and maintenance plans

The system is intended to operate under different conditions, strictly under abnormal conditions, to bring the system to normality. The responses drawn from the simulation supported the intended performance under the varying conditions. Power variation compensations, frequency issues addressed, and climate conditions affecting the system stability operation are addressed, bringing the system into a good expected performance state.

These findings demonstrate that the wind farm integrated BESS model aligns with the research objectives by enhancing grid stability, optimising energy utilisation, and providing a reliable and sustainable energy solution. The study validates the proposed system's technical and economic feasibility and establishes its relevance for addressing the growing demand for renewable energy integration.

The research aim and objectives were met, systematically proving that the Wind Farm stability can be achieved, and good performance is in place , mitigating FRT and power variation. The whole study supported the proposed integration technology of BESS to the Wind Farm

6.3. Conclusions drawn from the study

The conclusion drawn from the study is that the integration of this technology is possible and capable of performing the expected outcomes, thus meeting the aim and objectives outlined in this work. Performance of a Wind Farm integrated with BESS technology has proven to solve technical problems that are expected within the renewable energy space, strictly wind farms, as they cannot perform to their best due to climate issues. The economic study further shows the benefits of combining wind farms with BESS. The system maximises financial rewards by using optimisation models that take peak-valley electricity prices into account and minimise the risks related to power generation unpredictability. This makes a strong case for wider deployment by proving that hybrid wind-BESS systems are technically possible and profitable. Additionally, this technology concluded that the integration helps to improve power outputs, power quality mostly mitigates curtailments, and all this combined leads to having stable grid integration and better economic achievements.

Another observation was that while this technology can be heavy on investment during initial stages, the end results from operations are far better than without BESS integration; the wind farm lifespan itself can also be extended due to this technology integration. There is also less worry when performing maintenance and other system outages as the BESS can be used to plan those tasks without hindering the supply to the consumers, mitigating the race between production and planned maintenance schedules. All these possibilities and capabilities require an accurate BESS modelling and control strategy mechanism as it is essential to minimise degradation, thus improving the lifespan of the technology integration.

6.4. Implications of the Research

The importance of this research in furthering the integration of renewable energy is highlighted by its consequences, which cut across technological, economic, and policy dimensions.

Technically speaking, the study emphasises how important BESS is to reducing power fluctuations and improving grid stability, providing a workable answer to the problems caused by wind energy's intermittent nature. The dependability and resilience of renewable energy systems are increased by BESS's capacity to increase wind turbines' FRT capabilities, guaranteeing a continuous power supply during grid outages. BESS is essential to updating grid facilities to handle the growing share of renewable energy.

The study shows that hybrid wind-BESS systems are economically feasible, with optimisation models optimising wind energy projects' financial returns. The profitability of renewable energy investments is increased by these systems, which transform excess energy into high-value output by taking advantage of peak-valley electricity prices. This has important ramifications for energy stakeholders, offering a strong financial case for adding BESS to wind farms and hastening the switch to sustainable energy systems.

The results highlight the necessity of regulatory frameworks conducive to deploying hybrid energy systems from a policy standpoint. Policymakers can use the study's conclusions to provide tax breaks or other incentives to incentivise investment in renewable energy and BESS technologies. The report also emphasises how crucial uniform grid codes are to smoothly integrate hybrid systems and develop a more unified and effective energy network.

Additionally, the study has wider ramifications for climate change mitigation and sustainability. The suggested hybrid system helps the world's shift to greener energy sources by stabilising the output of renewable energy, which lessens dependency on fossil fuels and helps meet greenhouse gas emission reduction goals. This supports the importance of renewable energy in attaining a low-carbon future and aligns with global sustainability goals.

This study offers a strong basis for tackling the policy, economic, and technical obstacles related to integrating renewable energy. It provides researchers, policymakers, and industry practitioners with useful insights that spur innovation and aid in creating robust and sustainable energy infrastructures.

6.5. Recommendations for Industry and Policy

This study identifies several crucial areas where policymakers and industry stakeholders may take concrete measures to improve the efficiency of renewable energy systems and hasten the integration of wind farm-integrated BESS systems. The energy sector must use cutting-edge optimisation methods for BESS functioning and size. To enhance energy dispatch, storage utilisation, and grid stability, industry players ought to invest in creating and implementing predictive algorithms that use real-time data. For BESS systems that meet the unique requirements of wind energy projects to be implemented successfully, cooperation between technology providers and developers of renewable energy is required. In order to guarantee the efficient behaviour of the technology during grid fluctuations and other issues, the simulation of such issues has been rolled out and the integration continued to operate efficiently during these failures. The developers must dwell on the employment of this integration and invest more to fine-tune the system to get more out of it. This is an everyday learning experience and can better the industry for future generations

The simulation was strictly guided by policies employed in operations around the utility space. This accounts for grid code compliance, environmental impact and supporting curtailment schedules that are imposed due to affected species around the chosen site. Two important areas for policy involvement are grid code compliance and standardisation. To ensure technological compatibility and operational efficiency, governments should create and implement standardised grid codes that make it easier to integrate hybrid systems.

To have a reputable industry for grid operators and renewable energy investors, the optimisation of hybrid systems must be promoted, as results have shown to favour most of the issues that are exemplified and experienced out in the field. This is evident from how South Africa has rolled out BESS projects throughout the country, targeting areas with grid availability for connection and evacuation of power, and also areas with high demand for power supply, strictly where the grid imbalance is observed.

Sustainability and environmental concerns are mostly the primary concern when developing these types of technologies; therefore, lifecycle assessment and investment interest are also part of the concerns to validate the deployment of the integration. Integrating wind farm integrated BESS systems presents an innovative chance to promote global energy transitions and guarantee a cleaner, more resilient future. Ideas for Future Lines of Research. To improve scalability, efficiency, and sustainability, future research on wind farm integrated BESS systems should concentrate on developing several crucial areas. Beyond wind-BESS configurations, research should investigate integrating hybrid renewable energy systems.

The environmental impact of BESS deployment, especially regarding lifetime evaluations and end-of-life management, is another crucial topic that requires investigation. Research could concentrate on environmentally friendly battery material recycling and disposal techniques to reduce environmental impact. Energy storage technologies could be made much more sustainable by creating closed-loop recycling systems and finding substitute materials with less of an adverse effect on the environment. Future research ought to look into the socioeconomic effects of widespread BESS implementation. Examining the effects on community involvement, job creation, and the fair allocation of energy resources are all part of this.

The most interesting point from the results observations is the contribution to social sustainability and the assurance that adapting to a renewable energy system supports a vast range of groups. Research institutes must deploy more of these projects to demonstrate the need and address the crucial challenges while validating the BESS integration to wind farms.

6.6. Conclusion

This research successfully demonstrated the crucial role of the proposed technology in dealing with the observed variabilities of power generation. The results showed the highest potential for wind farm integrated technologies to bring grid stability, mitigation of power variations/fluctuations, thus improving economic need and operational possibilities of the renewable energy technology. Through the simulations performed, the system's response was evaluated, and the research confirms and concludes the effectiveness of the technology in normalising power output status, enhancing the FRT capability and also ensuring a stable energy supply, no matter the negative effects.

The benefits of this research are deeper and offer a wide feasibility of moving towards this technology, it brings high recommendations to the industry and investors to promote the deployment of hybrid systems in the country, considering the grid issues we have, power generating plants that we have and climate issues that we have no control over. The research aims to emphasise the importance of scalable and adaptable energy storage solutions brought by BESS integration to support renewable energy technologies, which align with the global sustainability goals and support the transition to green energy sources.

The future scholars should explore deeper advancements in BESS technologies and the integration further with renewable energy sources, and further refine the validations of the technology deployment. Addressing the technological downside to better the scientific approach when dealing with these systems, so we see more improvement and gain more from the use of these systems. The research then concludes that the study has laid a groundwork for more resilience and sustainable energy infrastructure.

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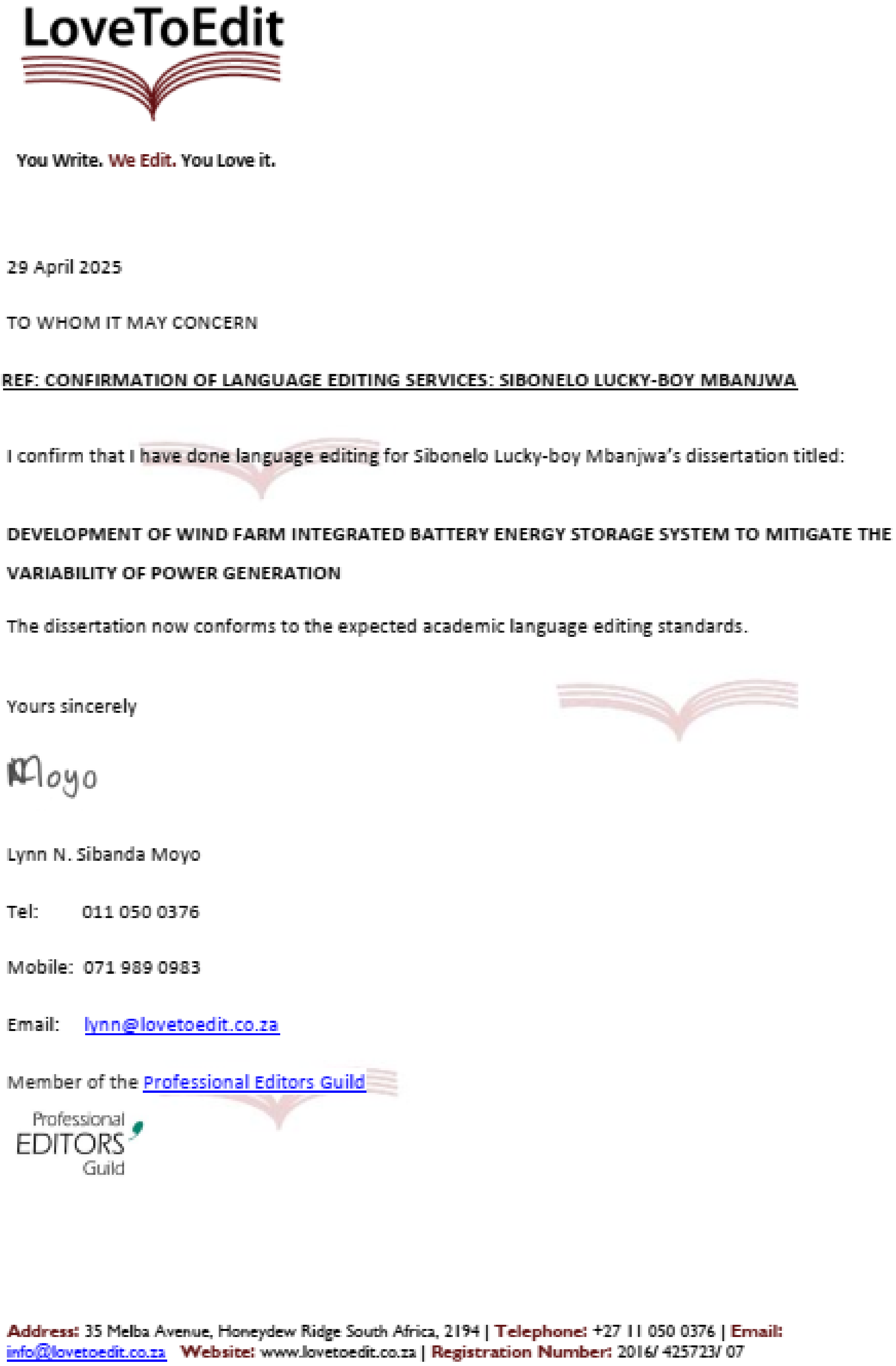
Appendix A

Language editing



LoveToEdit

You Write. We Edit. You Love it.

29 April 2025

TO WHOM IT MAY CONCERN

REF: CONFIRMATION OF LANGUAGE EDITING SERVICES: SIBONELO LUCKY-BOY MBANJWA

I confirm that I have done language editing for Sibonelo Lucky-boy Mbanjwa's dissertation titled:

DEVELOPMENT OF WIND FARM INTEGRATED BATTERY ENERGY STORAGE SYSTEM TO MITIGATE THE VARIABILITY OF POWER GENERATION

The dissertation now conforms to the expected academic language editing standards.

Yours sincerely

Moyo

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Appendix B

Wind farm and BESS parameters:

Report Documents

Project: Wind Farm Chaba	Study Case: 1. Base Case without BESS	Study Time: 2020/11/03 12:00:00

Table of Contents

Grid Summary

1 Grid Summary

Number of Grids: 1
Wind Farm Grid

2 Wind Farm Grid

2.1 Overview

Number of Voltage Levels	Number of Connected Grids	No. of Substations	No. of Busbars	No. of Terminals	No. of Lines
3	0	2	2	42	8
No. of 2-w Trfs.	No. of 3-w Trfs.	No. of 4-w Trfs.	No. of syn. Machines	No. of asyn. Machines	No. of Static Generators
8	0	0	0	0	8
No. of PV Systems	No. of Loads	No. of SVS	No. of Shunts/Filters	No. of Other Elements	No. of Isolated Areas
0	1	0	1	1	1
No. of Unsupplied Isolated Areas					
0					

2.2 Power Summary

Generators, Active Power MW	Generators, Reactive Power Mvar	Generators, Apparent Power MVA
25.0	-7.2	26.0
Generators, Nominal Active Power MW	Generators, Nominal Reactive Power Mvar	Generators, Nominal Apparent Power MVA
28.7	12.8	31.4
Generators, difference between maximum and actual active power MW	Generators, difference between maximum and actual reactive power Mvar	
0.0	0.0	
Loads, Active Power MW	Loads, Reactive Power Mvar	Loads, Apparent Power MVA
15.0	0.0	15.0
Loads, Nominal Active Power MW	Loads, Nominal Reactive Power Mvar	Loads, Nominal Apparent Power MVA
15.0	0.0	15.0
Loads, difference between nominal and actual active power MW	Loads, difference between nominal and actual reactive power Mvar	
0.0	0.0	
Motor Loads, Active Power MW	Motor Loads, Reactive Power Mvar	Motor Loads, Apparent Power MVA
0.0	0.0	0.0
Losses, Active Power MW	Losses, Reactive Power Mvar	
0.5	0.9	
0.4	1.1	

Losses, Active Power (no load) MW	Losses, Reactive Power (no load) Mvar	
0.1	-0.3	
External Networks, Active Power MW	External Networks, Reactive Power Mvar	External Networks, Apparent Power MVA
-9.5	8.1	12.5

2.3 Additional Power Summary

Compensation, L Mvar	Compensation, C Mvar	
0.0	0.0	
Generators, Power Factor -	Loads, Power Factor -	Motor Loads, Power Factor -
0.961	1.000	0.000

2.4 Maximum/Minimum Summary

Maximum voltage of all terminals p.u.	Minimum voltage of all terminals p.u.	
1.048	0.972	
Maximum Loading %		
120.1		

2.5 Interchange Power Flow Summary

Interchange Power Flow To Other Grids	Interchange Flow, Active Power MW	Interchange Flow, Reactive Power Mvar
Total	0.0	0.0

Zone Summary Charts

3 Zone Comparison Charts

Voltage and Loading Violations

Loading Violations

Maximum Loading of Branch Elements
80 %

Name	Element type	Loading %	Station\Busbar	Total Apparent Power MVA	Positive-Sequence Current, Magnitude kA	Positive-Sequence Current, Magnitude p.u.
Cable Grid Connection	Line	120.1	Distribution Network Substation\Busbar PoC	25.8	0.678	1.201
			Wind Farm Substation\Busbar	25.9	0.678	1.201
BESS	Static Generator	105.3	Wind Farm Substation\Busbar	7.9	0.207	1.052
Trf 1.1	2-Winding Transformer	88.8	MV 1.1	2.6	0.068	0.865
			LV 1.1	2.6	2.230	0.888
Trf 1.2	2-Winding Transformer	88.8	MV 1.2	2.6	0.068	0.865
			LV 1.2	2.6	2.228	0.888
Trf 1.3	2-Winding Transformer	88.7	MV 1.3	2.6	0.068	0.865
			LV 1.3	2.6	2.228	0.887
Trf 2.1	2-Winding Transformer	88.3	MV 2.1	2.6	0.068	0.860
			LV 2.1	2.6	2.217	0.883
Trf 2.2	2-Winding Transformer	88.2	MV 2.2	2.6	0.068	0.859
			LV 2.2	2.6	2.214	0.882
Trf 2.3	2-Winding Transformer	88.1	MV 2.3	2.6	0.068	0.859
			LV 2.3	2.6	2.212	0.881
Trf 2.4	2-Winding Transformer	88.0	MV 2.4	2.6	0.067	0.857
			LV 2.4	2.6	2.209	0.880
Cable 2.1	Line	84.2	Wind Farm Substation\Busbar	10.2	0.268	0.839
			MV 2.1	10.4	0.269	0.842

Total System Summary

7 Summary Grid

7.1 Overview

Number of Voltage Levels	Number of Connected Grids	No. of Substations	No. of Busbars	No. of Terminals	No. of Lines
3	0	2	2	42	8
No. of 2-w Trfs.	**No. of 3-w Trfs.**	**No. of 4-w Trfs.**	**No. of syn. Machines**	**No. of asyn. Machines**	**No. of Static Generators**
8	0	0	0	0	8
No. of PV Systems	**No. of Loads**	**No. of SVS**	**No. of Shunts/Filters**	**No. of Other Elements**	**No. of Isolated Areas**
0	1	0	1	1	1
No. of Unsupplied Isolated Areas					
0					

7.2 Power Summary

Generators, Active Power MW	Generators, Reactive Power Mvar	Generators, Apparent Power MVA
25.0	-7.2	26.0
Generators, Nominal Active Power MW	**Generators, Nominal Reactive Power Mvar**	**Generators, Nominal Apparent Power MVA**
28.7	12.8	31.4
Generators, difference between maximum and actual active power MW	**Generators, difference between maximum and actual reactive power Mvar**	
0.0	0.0	
Loads, Active Power MW	**Loads, Reactive Power Mvar**	**Loads, Apparent Power MVA**
15.0	0.0	15.0
Loads, Nominal Active Power MW	**Loads, Nominal Reactive Power Mvar**	**Loads, Nominal Apparent Power MVA**
15.0	0.0	15.0
Loads, difference between nominal and actual active power MW	**Loads, difference between nominal and actual reactive power Mvar**	
0.0	0.0	
Motor Loads, Active Power MW	**Motor Loads, Reactive Power Mvar**	**Motor Loads, Apparent Power MVA**
0.0	0.0	0.0
Losses, Active Power MW	**Losses, Reactive Power Mvar**	
0.5	0.9	

0.4	1.1	
Losses, Active Power (no load) MW	Losses, Reactive Power (no load) Mvar	
0.1	-0.3	
External Networks, Active Power MW	External Networks, Reactive Power Mvar	External Networks, Apparent Power MVA
-9.5	8.1	12.5

7.3 Additional Power Summary

Compensation, L Mvar	Compensation, C Mvar	
0.0	0.0	
Generators, Power Factor -	Loads, Power Factor -	Motor Loads, Power Factor -
0.961	1.000	0.000

7.4 Maximum/Minimum Summary

Maximum voltage of all terminals p.u.	Minimum voltage of all terminals p.u.	Maximum Loading %
1.048	0.972	120.1

Project Overview

Project

Name	Wind Farm Chaba

Project Library	
Element type	Number
User Defined Models	5
Report Template	0
Tablular Report	0

Network Model	
Element type	Number
Grids	1
Operation Scenarios	2
Variations	2

Study Cases	
Number	18
Active Study Case	
Name	1. Base Case without BESS
Study Time	2020/11/03 12:00:00
Breaker reduction	Enhanced mode
Calculate results for all breakers	Yes
Solution of linear equations	Direct method
Name of Active Scenario	None
Name of Recording Variation	None
Name of Recording Expansion Stage	None
Element type	Number
Active Grids	1
Active Variations	0
Active Triggers	0

Load Flow Calculation

Calculation Method	AC Load Flow, balanced, positive sequence	Active Power Control	as Dispatched
Automatic tap adjustment of transformers	No	Balancing	by reference machine
Automatic tap adjustment of shunts	No	Load Flow Method	Newton-Raphson (Power Equations, classical)
Automatic tap adjustment of phase shifters	No	Max. Acceptable Load Flow Error:	
Consider active power limits	Yes	Bus Equations (HV)	1.0 kVA
Consider reactive power limits	Yes	Bus Equations (MV)	1.0 kVA
Temperature Dependency at	Operating temperature	Bus Equations (LV)	1.0 kVA
Consider Voltage Dependency of Loads	No	Model Equations	0.1 %
Feeder Load Scaling	No		

Grid Summary Charts

8 Grid Comparison Charts

8.1 Generators

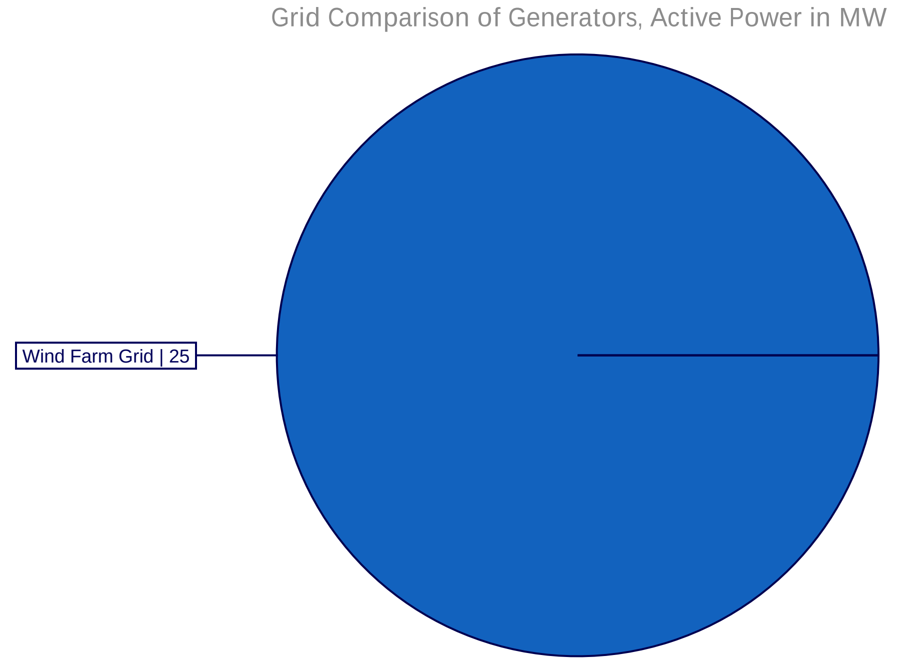

Figure 1: Generators, Active Power

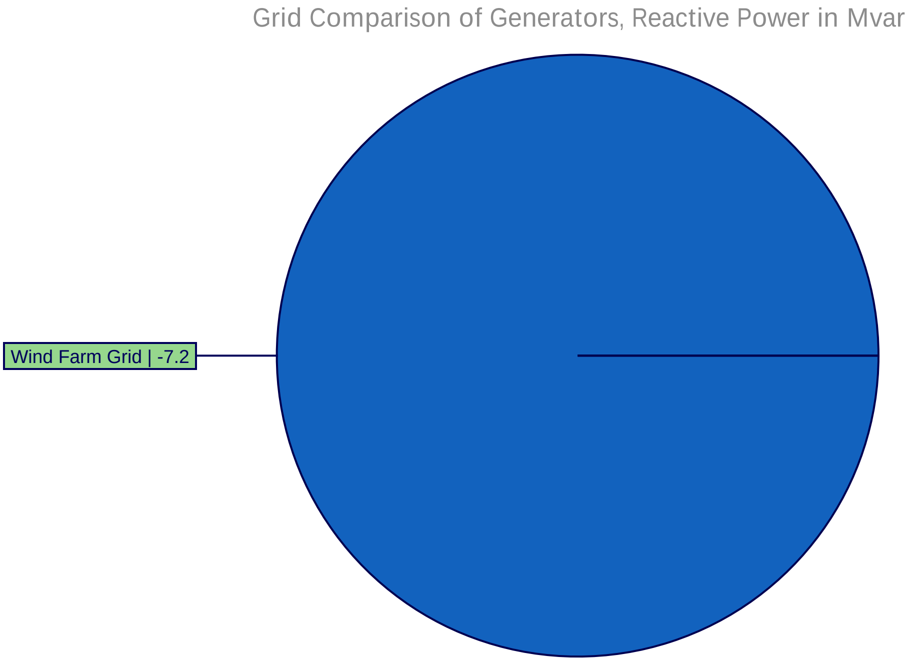

Figure 2: Generators, Reactive Power

8.2 Loads

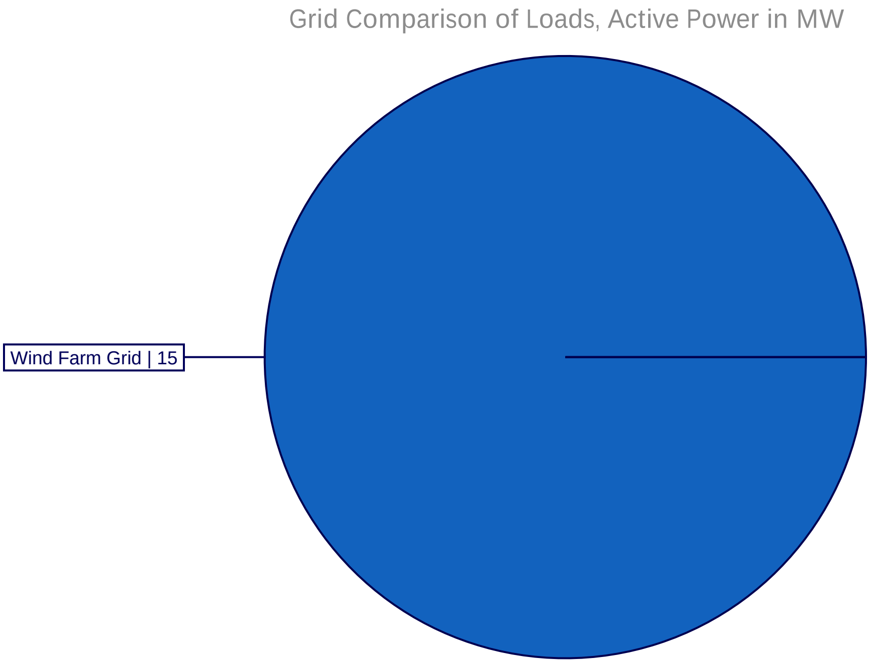

Figure 3: Loads, Active Power

Figure 4: Loads, Reactive Power

8.3 Losses

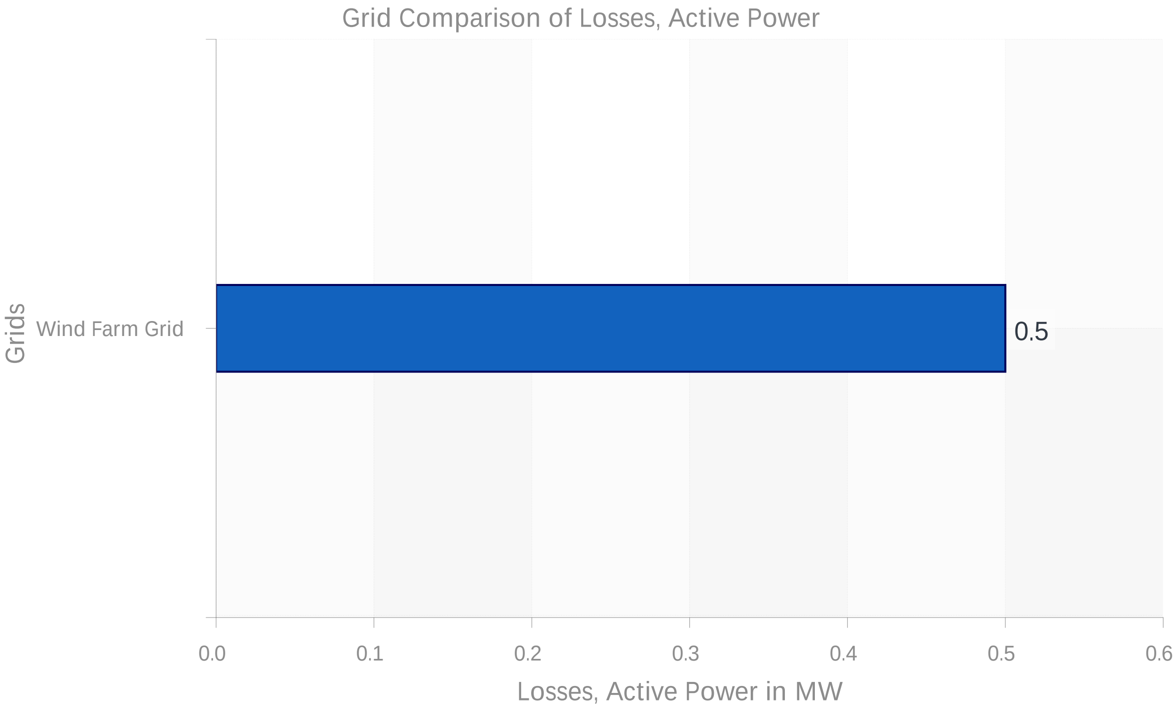

Figure 5: Losses, Active Power

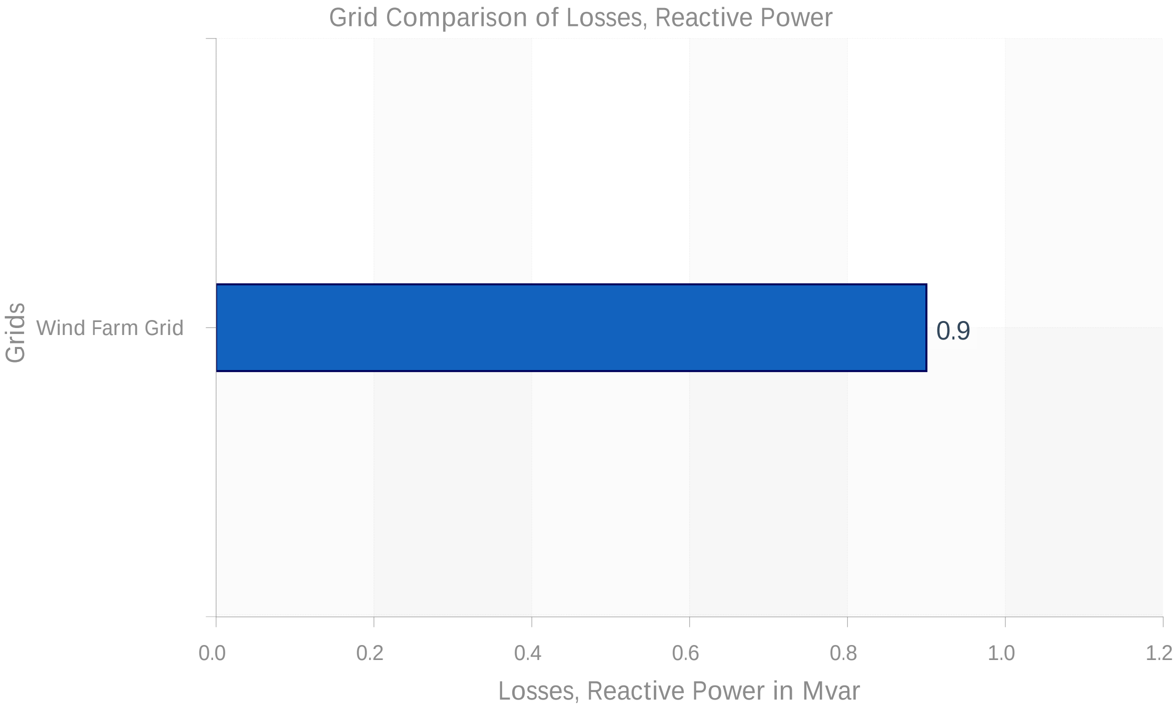

Figure 6: Losses, Reactive Power

8.4 Compensation

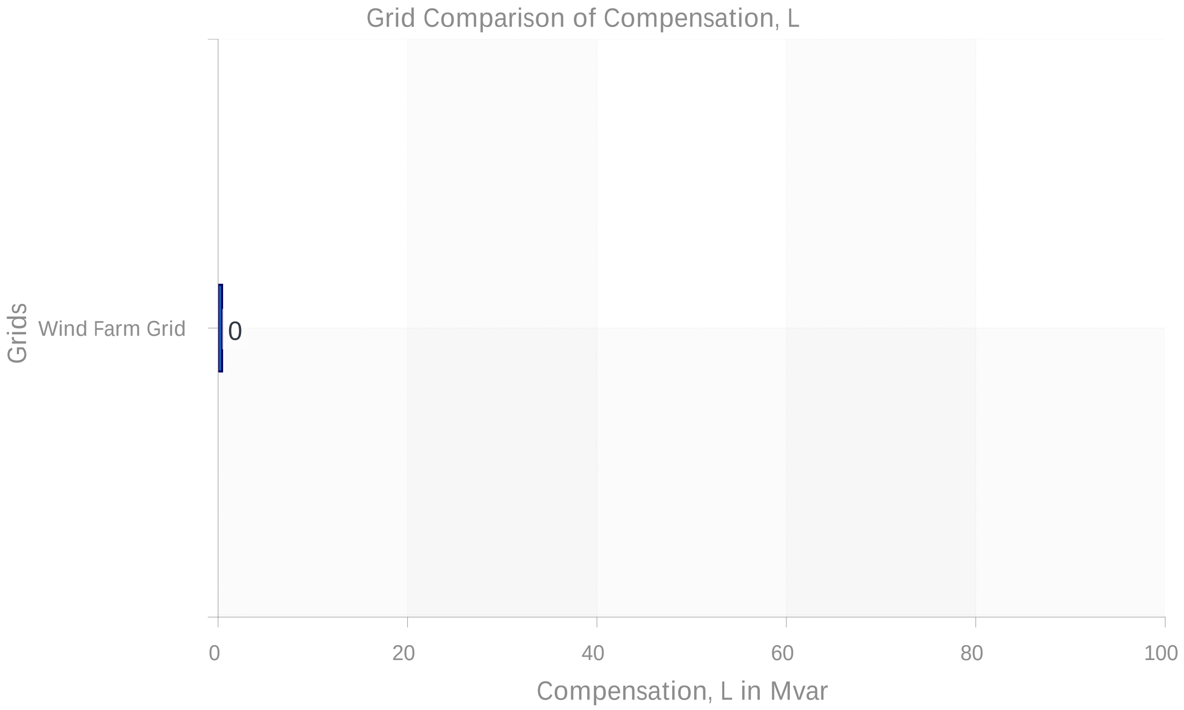

Figure 7: Compensation, L

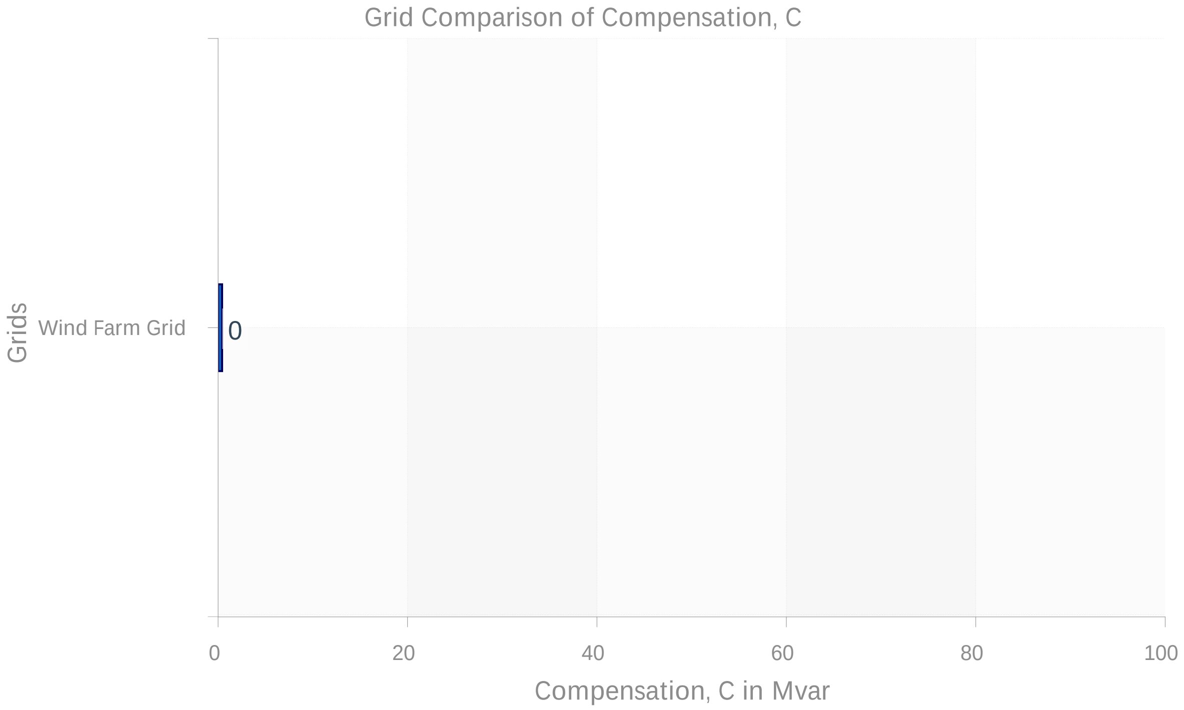

Figure 8: Compensation, C

8.5 Voltage Maximum/Minimum

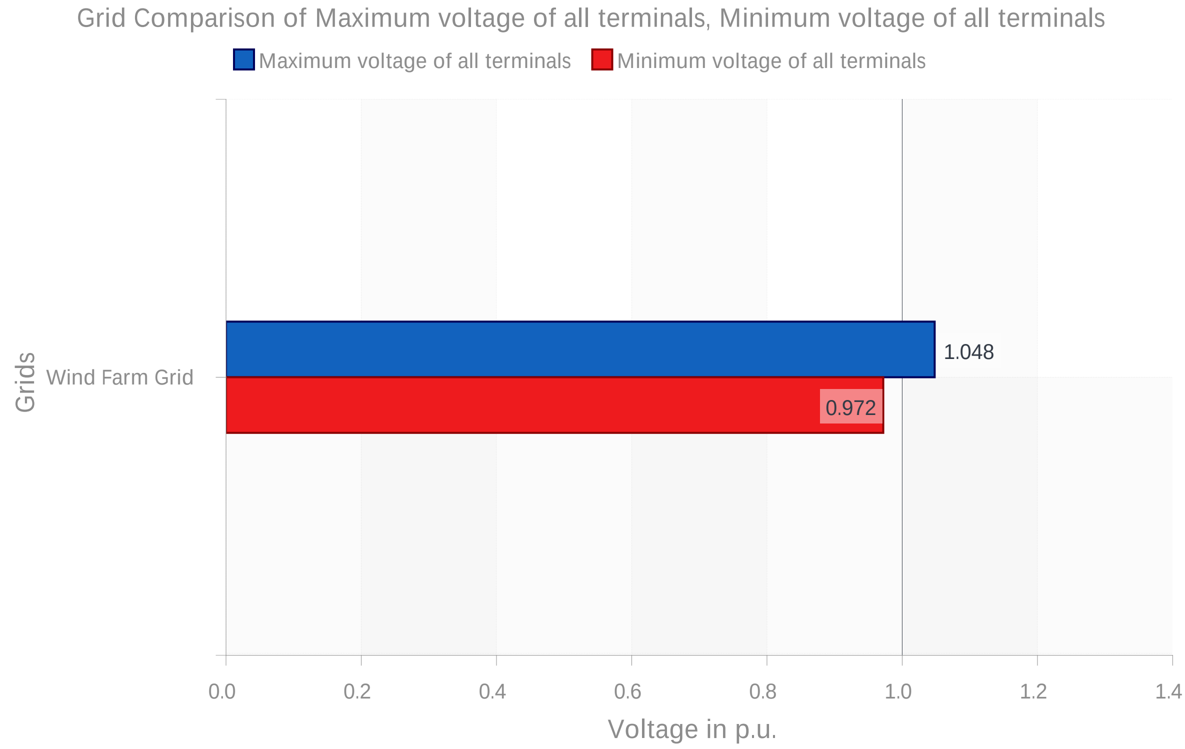

Figure 9: Maximum voltage of all terminals, Minimum voltage of all terminals

8.6 Maximum Loading

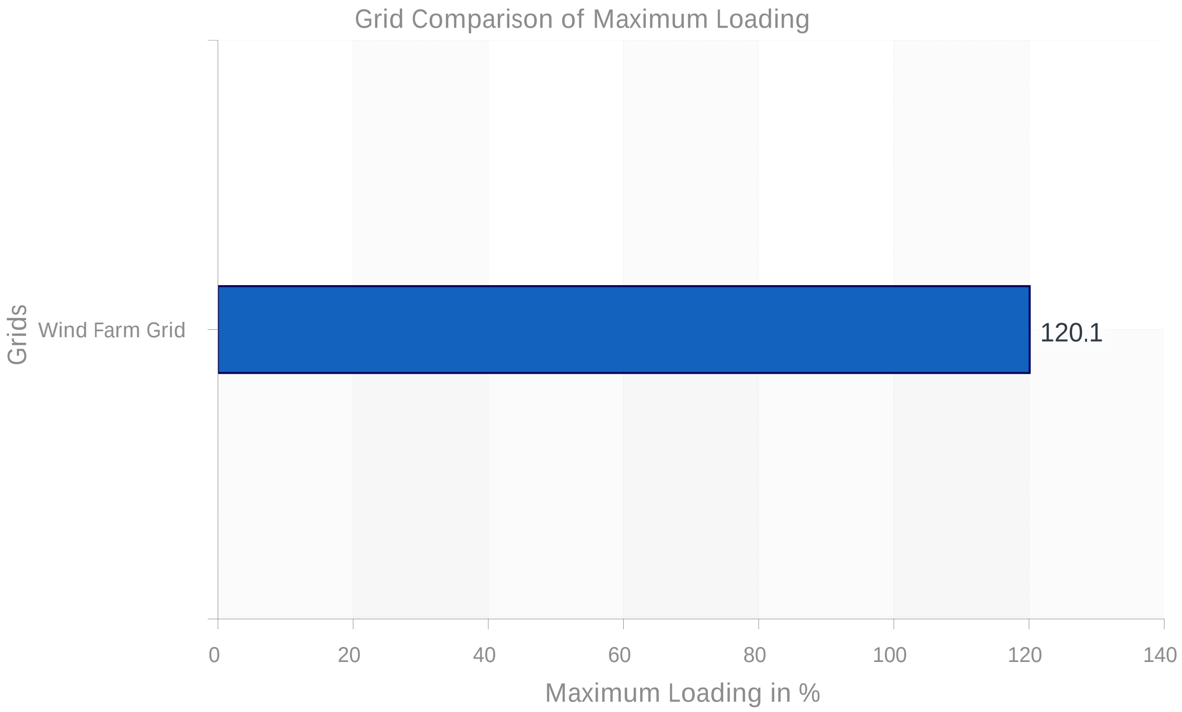

Figure 10: Maximum Loading

9 Grid Interchange Charts

9.1 Wind Farm Grid

No interchange results available

General Settings

Project Settings

Validity Period	
Start Time	1970/01/01 02:00:00
End Time	2106/02/07 08:28:15

Formats and Units			
Input Variables			
Units		Metric	
Lines/Cables Length unit, m		k	
Loads/Asyn. and DC Machines P, Q, S unit, VA,W,var		M	
Static Generators/Synchr. Machines P, Q, S unit, VA,W,var		M	
Currency unit		USD	
Default frequency		50 Hz	
Output Variables			
Load Flow and Simulation			
Volt, V	k	Decimal places	1
Ampere, A	k	Decimal places	3
W, VA, var	M	Decimal places	1
Short-Circuit			
Volt, V	k	Decimal places	1
Ampere, A	k	Decimal places	3
W, VA, var	M	Decimal places	1
Percent (%) decimal places		1	
Per unit (p.u.) decimal places		3	
Degree (angle) decimal places		1	
Energy decimal places		1	
Currency decimal places		2	
Decimal places for other units		4	

Calculation Options

General	
Base Apparent Power	100.0 MVA
HV voltage level	66.0 kV
MV voltage level	1.0 kV
Min. Resistance rmin	1.000 p.u. (based on 1e+12 * 1MVA)
Min. Conductance gmin	11.000 p.u. (based on 1e-9 * 1MVA)
Threshold Impedance for Z-model	1.000 p.u. (based on 1e+6 * 1MVA)

Topology		
Settings for slack assignment	Auto slack assignment	Method 1
	Priority for Reference Machines	Rated Power
	Auto slack assignment for areas without connection to fictitious border grid	Yes
Determination of supplying transformers	Considered transformers	Only those located in stations
Automatic Out of Service Detection	No	

Lines/Branches	
Calculation of symmetrical components for untransposed lines	Method 1
Earth wire reduction of towers	first reduce then transpose (V14.0)
Consider line compensation current for line loading calculation	No
Consider bay loading for branch loading calculation	Yes

Result file	
Type	Binary file
Maximum read buffer size	200 MB
Auto detect maximum number of reading threads (hardware dependent)	Yes

Miscellaneous		
Switching Actions	Isolate with earthing	Yes
	Isolate opens circuit-breakers only	No
Planned Outages	Consider automatically upon study case activation	No
	Creation	Create IntPlannedout (Supported since version 2017)
	Application sequence	Time-based application (time before priority)

Data Verification

Nominal Voltage Check		
Max. allowed difference over Lines/Switches/Fuses	for Lines	10.0 %
	for Switches and Fuses	10.0 %
Max. allowed deviation from Terminal voltage	for Transformers	50.0 %
	for other Elements	50.0 %
Line couplings		
Allowable difference in lengths of lines	1.0 %	

User Settings

Parallel Computing		
Allow Parallel Computing		Yes
Allow to preallocate processes in the background		No
Actual number of processes to be used	Use all allowed processes	Max. number of parallel processes allowed for this user is 24.
Max. waiting time for process response		50 s
Transfer complete project to all processes		Yes
Miscellaneous		
Decimal Symbol		from System ('.')
Optimisation		
Built-in mixed-integer linear programming solvers		
Cbc		Yes
lp_solve		Yes
Available external mixed-integer linear programming solvers		
CPLEX		No
Gurobi		No

External Applications

Python	Interpreter	selected by version	3.13
PDF Viewer	Used viewer	system viewer	
C/C++ Compiler	Version	MinGW	

Feeder Summary

Name	First branch component	Total Active Power, Infeed MW	Total Load, Active Power MW	Generators, Active Power MW	Losses, Active Power MW	Maximum Loading %	Minimum voltage of all terminals p.u.	Maximum voltage of all terminals p.u.	Max. Voltage Drop %	Max. Voltage Rise %
Wind Farm	Cable Grid Connection	-24.5	0.0	25.0	0.5	120.1	0.972	1.048	2.8	4.8

Edge Elements

10 Grids

10.1 Wind Farm Grid

Wind Farm Grid

Name	Element type	Loading %	Terminal	Total Active Power MW	Total Reactive Power Mvar	Total Power Factor -	Current, Magnitude kA	Current, Magnitude p.u.
Cable Grid Connection	Line	120.1	Busbar PoC	-24.5	8.1	-0.949	0.678	1.201
			Busbar	24.6	-8.1	0.950	0.678	1.201
BESS	Static Generator	105.3	Busbar	7.5	-2.5	0.950	0.207	1.052
Trf 1.1	2-Winding Transformer	88.8	MV 1.1	-2.5	0.8	-0.947	0.068	0.865
			LV 1.1	2.5	-0.7	0.965	2.230	0.888
Trf 1.2	2-Winding Transformer	88.8	MV 1.2	-2.5	0.8	-0.947	0.068	0.865
			LV 1.2	2.5	-0.7	0.965	2.228	0.888
Trf 1.3	2-Winding Transformer	88.7	MV 1.3	-2.5	0.8	-0.947	0.068	0.865
			LV 1.3	2.5	-0.7	0.965	2.228	0.887
Trf 2.1	2-Winding Transformer	88.3	MV 2.1	-2.5	0.8	-0.947	0.068	0.860
			LV 2.1	2.5	-0.7	0.965	2.217	0.883
Trf 2.2	2-Winding Transformer	88.2	MV 2.2	-2.5	0.8	-0.947	0.068	0.859
			LV 2.2	2.5	-0.7	0.965	2.214	0.882
Trf 2.3	2-Winding Transformer	88.1	MV 2.3	-2.5	0.8	-0.947	0.068	0.859
			LV 2.3	2.5	-0.7	0.965	2.212	0.881
Trf 2.4	2-Winding Transformer	88.0	MV 2.4	-2.5	0.8	-0.947	0.067	0.857
			LV 2.4	2.5	-0.7	0.965	2.209	0.880
Cable 2.1	Line	84.2	Busbar	-9.7	3.2	-0.951	0.268	0.839
			MV 2.1	9.9	-3.2	0.951	0.269	0.842
WTG 2.4	Static Generator	75.7	LV 2.4	2.5	-0.7	0.965	2.209	0.772
WTG 2.3	Static Generator	75.7	LV 2.3	2.5	-0.7	0.965	2.212	0.773

Name	Element type	Loading %	Terminal	Total Active Power MW	Total Reactive Power Mvar	Total Power Factor -	Current, Magnitude kA	Current, Magnitude p.u.
WTG 2.2	Static Generator	75.7	LV 2.2	2.5	-0.7	0.965	2.214	0.774
WTG 2.1	Static Generator	75.7	LV 2.1	2.5	-0.7	0.965	2.217	0.775
WTG 1.3	Static Generator	75.7	LV 1.3	2.5	-0.7	0.965	2.228	0.778
WTG 1.2	Static Generator	75.7	LV 1.2	2.5	-0.7	0.965	2.228	0.779
WTG 1.1	Static Generator	75.7	LV 1.1	2.5	-0.7	0.965	2.230	0.779
Cable 1.1	Line	63.7	Busbar	-7.4	2.4	-0.951	0.203	0.635
			MV 1.1	7.4	-2.5	0.950	0.204	0.637
Cable 2.3	Line	42.1	MV 2.3	4.9	-1.6	0.950	0.135	0.421
			MV 2.1	-4.9	1.6	-0.952	0.134	0.420

Area Summary Charts

11 Area Comparison Charts

Busbars/Terminals

12 Parameters

Lower Limit of Terminal Voltage p.u.	Upper Limit of Terminal Voltage p.u.	Lower Limit of Connected Elements Active Power MW	Upper Limit of Connected Elements Active Power MW	Show Connected Elements without Active Power	Minimum Loading of Connected Elements %
0.9	1.1	-10000	10000	Yes	30

13 Grids

13.1 Wind Farm Grid

Wind Farm Grid

13.1.1 Substations

Substation: Distribution Network Substation

Distribution Network Substation

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
Busbar PoC	22.0	1.000	22.0	-0.0

Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Cable Grid Connection	Line	-24.5	8.1	-0.949	0.678	120.1
22 kV Grid	External Grid	-9.5	8.1	-0.762	0.329	
Customer Load	General Load	15.0	0.0	1.000	0.394	

Substation: Wind Farm Substation

Wind Farm Substation

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
Busbar	22.0	1.001	22.0	0.1

Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Cable Grid Connection	Line	24.6	-8.1	0.950	0.678	120.1
BESS	Static Generator	7.5	-2.5	0.950	0.207	105.3
Cable 2.1	Line	-9.7	3.2	-0.951	0.268	84.2
Cable 1.1	Line	-7.4	2.4	-0.951	0.203	63.7

13.1.2 Terminals

Terminals

Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.	Line-Line Voltage, Magnitude kV	Voltage, Angle deg
MV 1.1	22.0	1.007	22.1	0.5

Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
Trf 1.1	2-Winding	-2.5	0.8	-0.947	0.068	88.8

		Transformer					
	Cable 1.1	Line	7.4	-2.5	0.950	0.204	63.7
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
MV 1.2	22.0	1.007		22.2		0.5	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Trf 1.2	2-Winding Transformer	-2.5	0.8	-0.947	0.068	88.8
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
MV 1.3	22.0	1.008		22.2		0.5	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Trf 1.3	2-Winding Transformer	-2.5	0.8	-0.947	0.068	88.7
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
MV 2.1	22.0	1.012		22.3		0.8	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Trf 2.1	2-Winding Transformer	-2.5	0.8	-0.947	0.068	88.3
	Cable 2.1	Line	9.9	-3.2	0.951	0.269	84.2
	Cable 2.3	Line	-4.9	1.6	-0.952	0.134	42.1
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
MV 2.2	22.0	1.013		22.3		0.9	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Trf 2.2	2-Winding Transformer	-2.5	0.8	-0.947	0.068	88.2
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude kV		Voltage, Angle deg	
MV 2.3	22.0	1.014		22.3		0.9	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Trf 2.3	2-Winding Transformer	-2.5	0.8	-0.947	0.068	88.1
	Cable 2.3	Line	4.9	-1.6	0.950	0.135	42.1
Terminal	Nominal Line-Line Voltage kV	Voltage, Magnitude p.u.		Line-Line Voltage, Magnitude		Voltage, Angle deg	

				kV			
MV 2.4	22.0	1.016		22.3		1.0	
	Name	Element type	Active Power MW	Reactive Power Mvar	Power Factor -	Current, Magnitude kA	Loading %
	Trf 2.4	2-Winding Transformer	-2.5	0.8	-0.947	0.067	88.0