

Modelling and analysis of battery energy storage
integrated wind power system with multi-source
converter using software PSCAD

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vorgelegt von

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Abstract

Wind energy, a prominent renewable resource, has seen rapid expansion, but this growth introduces complexities in maintaining power system stability due to the variable nature of wind. This unpredictability necessitates energy storage solutions to balance supply and demand effectively. Traditional wind power systems, lacking storage capabilities, have required grid expansions and modernizations to manage power fluctuations. A promising approach, suggested in this thesis, involves integrating a multisource converter-based wind energy system with battery energy storage, making wind turbines more dispatchable by ensuring constant power through quick charging and discharging responses.

Wind Energy Conversion Systems (WECS) have proven more cost-effective than fossil fuels, making research into wind power increasingly crucial. In this context, a unique model has been developed, integrating a battery energy storage system at the DC-link of a Type-4 wind turbine. The control system manages power output to the grid based on grid demand and wind power availability, while maintaining stable DC-link voltage. Simulation results, conducted using PSCAD/EMTDC software, demonstrated effective control of the system under various wind conditions and grid requirements. The simulation results illustrate the control of a DC-link integrated battery energy storage system at different set point wind speeds and set point grid power as well as with time series wind data. In addition State Of Charge(SOC) permit control approach has also been illustrated.

This research investigates the effectiveness of an active power management strategy in maintaining the stability of power system comprising a Wind Turbine Generator (WTG) and Battery Energy Storage System (BESS). By linking a BESS at the DC-link of a permanent magnet synchronous generator (PMSG) based wind power system, the system ensures operational integrity during power generation fluctuations. The study proposes using energy storage to support system strength, enabling high penetration of renewables in weak networks.

The research present approache for fault ride-through in grid-connected Type-4 wind turbines with fully rated converter utilizing battery storage for enhanced LVRT capabilities during dynamic grid conditions to overcome power curtailment issue by utilizing charging capability of battery system in case of DC link overshoot problem during faults dynamics. The study underscores the importance of optimizing BESS to stabilize system operations, maintain power quality, and ensure grid stability during faults.

The findings of this research can be summarized in some of the main achievements. Firstly, this topology represents a forward-thinking approach to modern power grids,

emphasizing sustainability, efficiency, and cost-effectiveness. By balancing renewable energy generation with advanced storage and demand management, it can provide smooth power during on-peak demand and can save excess power from the wind side during off-peak demand, and provide economic advantages regarding unit prices of power delivery it can deliver reliable and economical electricity.

Secondly, the design of the battery system will be such that it can be easily installed on a rack inside the tower. This control system represents a sophisticated approach to modern energy management, particularly in grids with high penetration of renewable energy sources. By focusing on DC-link voltage stability and the efficient use of BESS, it helps create a more reliable electrical power system. Finally, the ride-through behavior under different disturbance scenarios has been analyzed and implemented by including additional control topologies. The investigation was carried out to enhance the existing voltage ride-through capability of the permanent magnet synchronous generator (PMSG) wind turbine by adding a BESS control system.

This research is a step forward in providing a base PSCAD EMT simulation model and technical concerns helpful for working in the renewable power system storage field and improvement in electrical power grid-side concerns, especially with the addition of supercapacitors with BESS addition to multi-source converter scheme control hierarchy.

Zusammenfassung

Die Windenergie, eine bedeutende erneuerbare Energiequelle, verzeichnet einen rasanten Zuwachs. Dieses Wachstum bringt jedoch aufgrund der variablen Windverhältnisse Komplexitäten bei der Aufrechterhaltung der Netzstabilität mit sich. Diese Unvorhersehbarkeit erfordert Energiespeicherlösungen, um Angebot und Nachfrage effektiv auszugleichen. Herkömmliche Windkraftanlagen verfügen nicht über Speicherkapazitäten und erfordern daher Netzerweiterungen und -modernisierungen, um Leistungsschwankungen zu bewältigen. Ein vielversprechender Ansatz, der in dieser Arbeit vorgeschlagen wird, ist die Integration eines auf einem Mehrquellen-Umrichter basierenden Windenergiesystems mit einem Batteriespeicher. Dadurch werden Windturbinen durch die Sicherstellung konstanter Leistung durch schnelle Lade- und Entladevorgänge besser planbar.

Windenergieumwandlungssysteme (WECS) haben sich als kostengünstiger als fossile Brennstoffe erwiesen, weshalb die Forschung im Bereich Windenergie zunehmend an Bedeutung gewinnt. In diesem Zusammenhang wurde ein einzigartiges Modell entwickelt, das ein Batteriespeichersystem in den Zwischenkreis einer Typ-4-Wind turbine integriert. Das Steuerungssystem steuert die Stromabgabe an das Netz basierend auf Netzbedarf und Windstromverfügbarkeit und sorgt gleichzeitig für eine stabile Zwischenkreisspannung. Simulationsergebnisse, die mit der Software PSCAD/EMTDC durchgeführt wurden, zeigten eine effektive Steuerung des Systems unter verschiedenen Windbedingungen und Netzanforderungen.

Die Simulationsergebnisse veranschaulichen die Steuerung eines DC-Link-integrierten Batteriespeichersystems bei unterschiedlichen Soll-Windgeschwindigkeiten und Soll-Netzleistungen sowie anhand von Winddaten aus Zeitreihen. Zusätzlich wurde der Ansatz zur Steuerung des Ladezustands (SOC) veranschaulicht.

In dieser Forschungsarbeit wird die Wirksamkeit einer aktiven Leistungsmanagementstrategie zur Aufrechterhaltung der Stabilität eines Stromsystems untersucht, das aus einem Windturbinengenerator (WEA) und einem Batteriespeichersystem (BESS) besteht. Durch die Verbindung eines BESS mit dem DC-Zwischenkreis eines auf einem Permanentmagnet-Synchrongenerator (PMSG) basierenden Windenergiesystems gewährleistet das System die betriebliche Integrität bei Schwankungen der Stromerzeugung. Die Studie schlägt den Einsatz von Energiespeichern zur Unterstützung der Systemstärke vor, um eine hohe Durchdringung von erneuerbaren Energien in schwachen Netzen zu ermöglichen.

In der Studie wird ein Ansatz für die Fehlerüberbrückung in netzgekoppelten Typ-4-Windturbinen mit voll ausgelegtem Umrichter vorgestellt, bei dem Batteriespeicher für verbesserte LVRT-Fähigkeiten unter dynamischen Netzbedingungen eingesetzt werden, um das Problem der Leistungsbeschränkung zu überwinden, indem die Ladefähigkeit des Batteriesystems im Falle eines Überschwingens der Gleichstromverbindung bei dynamischen Fehlern genutzt wird. Die Studie unterstreicht die Bedeutung der Optimierung von BESS zur Stabilisierung des Systembetriebs, zur Aufrechterhaltung der Stromqualität und zur Gewährleistung der Netzstabilität bei Störungen.

Die Ergebnisse dieser Forschung lassen sich in einigen wesentlichen Punkten zusammenfassen. Erstens stellt diese Topologie einen zukunftsweisenden Ansatz für moderne Stromnetze dar, der Nachhaltigkeit, Effizienz und Kosteneffizienz in den Vordergrund stellt. Durch die Kombination von erneuerbarer Energieerzeugung mit fortschrittlicher Speicherung und Bedarfssteuerung kann sie eine gleichmäßige Stromversorgung während Spitzenlastzeiten gewährleisten und überschüssigen Windstrom während Schwachlastzeiten speichern. Dies bietet wirtschaftliche Vorteile hinsichtlich der Stückpreise für die Stromlieferung und ermöglicht eine zuverlässige und wirtschaftliche Stromversorgung.

Zweitens ist das Batteriesystem so konzipiert, dass es problemlos auf einem Gestell im Turm installiert werden kann. Dieses Steuerungssystem stellt einen fortschrittlichen Ansatz für modernes Energiemanagement dar, insbesondere in Netzen mit hohem Anteil erneuerbarer Energiequellen. Durch die Fokussierung auf die Stabilität der Zwischenkreisspannung und die effiziente Nutzung von BESS trägt es zu einem zuverlässigeren Stromversorgungssystem bei. Schließlich wurde das Durchfahrverhalten unter verschiedenen Störungsszenarien analysiert und durch die Einbeziehung zusätzlicher Steuerungstopologien implementiert. Ziel der Untersuchung war es, die vorhandene Spannungsdurchfahrfähigkeit der Windkraftanlage mit Permanentmagnet-Synchrongenerator (PMSG) durch ein BESS-Steuerungssystem zu verbessern.

Diese Forschung ist ein Fortschritt bei der Bereitstellung eines grundlegenden PSCAD EMT-Simulationsmodells und technischer Aspekte, die für die Arbeit im Bereich der Speicherung erneuerbarer Energiesysteme und für Verbesserungen auf der Seite des Stromnetzes hilfreich sind, insbesondere durch die Ergänzung der Steuerungshierarchie von Mehrquellen-Konverterschemata um Superkondensatoren mit BESS.

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List of Abbreviations

Symbol	Description
RES	Renewable Energy Source
BESS	Battery Energy Storage System
SOC	State Of Charge
PMSG	Permanent Magnet Synchronous Generator
LVRT	Low Voltage Ride Through
WT	Wind Turbine
CB	Circuit Breaker
IG	Induction Generator
SG	Synchronous Generator
GB	Gear Box
TR	Transformer
VRR	Variable Rotor Resistance
MSC	Machine Side Converter
GSC	Grid Side Converter
WECS	Wind Energy Conversion System
ESS	Energy Storage System
VRE	Variable Renewable Energy
VSC	Voltage Source Converter
PCC	Point of Common Coupling
POC	Point of Connection
EMS	Energy Management System
BMS	Battery Management System
TOU	Time Of Use
SCR	Short Circuit Ratio
FRT	Fault Ride Through
PLL	Phase Locked Loop
WTG	Wind Turbine Generator

1 Introduction

1.1 Background and context

The fast-growing expansion of wind energy increases the complexities in balancing generation and demand in the power system. Due to the fluctuating wind characteristics, incorporating power from the wind turbines in the electrical grid has an effect on the power quality. The long-term unpredictability of renewable energy source like wind makes a certain amount of energy storage necessary. Previous wind power systems are operating without storage techniques because of some technical concerns like grid has to be expanded, and modernized, and one has to take measures to control or stabilize the grid during off-peak and on-peak load conditions [1]. A control system should be designed to control the power output to the grid depending upon the grid power requirements and wind power production by charging or discharging the battery storage system while also keeping a stable DC-link voltage.

In today's world, the direct link between the global population's growth and the escalating demand for electricity as a dependable and environmentally friendly energy source is undeniable. This growing reliance on electricity has given rise to pressing issues, including environmental concerns, power system stability challenges, and doubts about the reliability of our energy infrastructure. As a result, governments and researchers have been compelled to explore innovative solutions. Renewable energy sources, contingent upon geographical locations, offer a diverse array of options. Among these, wind energy emerges as a particularly promising source for meeting electricity demands. Wind farms employ various types of wind turbines, and in this context, the Permanent Magnet Synchronous Generator (PMSG) stands out.

Multi-source power generation systems that combine different renewable energy sources and energy storage systems offer an environmentally friendly alternative to conventional power generators for stand-alone applications. Also, the intermittency of these renewable resources necessitates the need for additional storage devices to balance the power generated and power demand [2]. For electrical power systems, the equilibrium of active power generated and consumed has to be maintained continuously. Therefore different controllers should be implemented in these power systems.

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The performance of these controllers should be analyzed, together with the dynamic behavior of the corresponding power plants, to determine the system's dynamic response to different disturbances. Some technical issues will be tackled in the planned research work by using a wind turbine with battery energy storage as an integral part of the power control system.

Renewable generation is interfaced to the grid through power electronics inverters. The short circuit strength at the connection point of a renewable generation plant, indicated by the short circuit ratio (SCR), is an important consideration. A low SCR is an indication of potential dynamic response issues. When the SCR at the point of connections (POC) drops too low, there is potential for overall system dynamic response concerns. When multiple inverter-interfaced devices are in close proximity to each other in a 'weak' area (low SCR), undesirable interactions (commonly known as control interactions - CI) can take place between these devices. In order to overcome these technical challenges, specific control strategies should be designed. System strength support using energy storage to enable high penetrations of resources to operate on weak networks.

Environmental concerns and the perpetual increase in demand for electricity have accelerated the utilization of renewable sources. In recent years climate changes and the limitation of fossil fuels have led to the development of new wind farms. As the penetration levels of wind farms increase new operational issues are raised. Plans for the development of wind energy among renewable sources offer a potential option. The Wind Energy Conversion System (WECS) has been determined to be more cost-effective than fossil fuels, whose prices are rising considerably more quickly. Due to the fact that WECS are primarily appropriate for wind power facilities, study into them has become more important. The primary goals of this study are to analyze the control topology and construct an effective Low Voltage Ride Threw, for the Permanent Magnet Synchronous Generator using battery storage. Fault ride-through refers to the ability of the wind farm to remain connected to the grid during the voltage dip. Fault events and voltage sag are critical complications in a weak grid as these circumstances can vastly affect the wind turbine functioning. Several methodologies have been proposed in recent years to address these problems. The purpose of this study is to optimize and strengthen the low voltage ride through (LVRT) capability of a wind turbine with the addition of a battery system and to stabilize the overall system operations in terms of power quality, grid voltages, and DC-link voltages during a fault event in different grid conditions.

1.2 Motivation

Continual growth in energy demand and intensified sustainability concern of fossil fuel-based electricity generation has thrust the escalation of renewable energy sources (RES), mainly photovoltaic and wind energy penetration, into the existing power system [3]. The government policy, social movement, advancement in renewable energy technologies, present-day installation scenarios, academic and industry research portfolios indicate the focus on an emission-free future electricity industry. Due to such resolutions, a similar momentum of RES penetration is expected to be maintained in future years. Regarding the realm of this work, incorporating the large-scale RES of alternating nature has brought additional dynamic and transient stability challenges in the existing electric grid [4]. RES with different degrees of operational characteristics than the conventional synchronous generators and inherent fluctuating behavior have increased the complexity of power system operation. Moreover, with RES penetration, the main electric grid encounters several technical difficulties such as violation of voltage limits, transmission congestions, peak generation-peak demand imbalance, the higher need for load-generation balance (spinning reserve), etc. In addition, the reduction of system inertial capability due to low inertial RES penetration is an increased area of concern, mainly their impact on power oscillation damping following a disturbance. Therefore, RES can provide clean energy but with the expense of stability distress [5]. Moreover, weather dependency of RES will result in power export within the network to maintain generation-demand balances and this situation will force certain transmission lines to be operated near their maximum capacity. With already-aged power grid infrastructures, the stability of the system is often at great risk while the highly loaded lines encounter disturbance. The accomplishment of a sustainable electricity industry would require the amalgamation of state-of-the-art technologies, operational practices, and sophisticated tools [6]. The target would be to incorporate the highest possible electricity generation from renewable energies, without raising stability and reliability concerns in the power system.

The collective global efforts on rehabilitating critical grid infrastructures, advancing electrical equipment design and control technology, simulating tools and embracing artificial intelligence are essential to achieve a major shift towards the future sustainable and smarter electric grid. The custom of power electronics devices to facilitate the higher amount of renewable energy throughputs and enhance power system stability are a common practice in many countries; mainly by means of different energy storage technologies [7]. The advancement in power electronics technology associated with an energy storage system has the ability to respond promptly. The

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present electric grid with added RES faces many technical challenges and all of the understanding and problems are yet to be resolved. Credible efforts have been put into the modelling of energy storage systems for utility-scale power system simulation in minimizing the adverse impact of Renewable energy systems [8]. Among many energy storage technologies, Battery Energy Storage System (BESS) has been used in dealing with the challenges of high penetration of RES in the electric power grid by enhancing power system stability. BESS is at the forefront mainly because of the technological advancement and reduction of battery costs in the last few years [9]. The modern world now trending towards the goal of expanding its energy supply and most importantly moving towards renewable energy sectors like wind and solar power sources. High potentials are to be seen above all in the use of wind and sun. Thus, by the upcoming years, countries having suitable wind conditions expect wind power capacity to be increased with a more economical and environment-friendly source of power. Due to favorable wind conditions mean wind speeds of up to 10 m/s at a height of 80 m above ground and a strong expansion of wind energy would be feasible. Parallel to the installation of wind and solar power plants also the grid has to be expanded, and modernized, and one has to take measures to control or stabilize the grid. Traditionally the stabilization of the electrical grid is carried out by large power stations by methods that have been used for many decades. There is a number of so-called ancillary services that are needed to operate a grid and for instance, keep voltage and frequency within certain narrow limits. With an increasing portion of renewable electrical power, the new power plants also have to contribute their share to the ancillary services. In the past, in countries with high penetration of renewables, this led to grid codes with requirements for grid connection of renewable generation systems. Well-known examples of grid-code requirements are power quality and low-voltage ride-through.

1.3 Key Objectives

The main objective of this research is to design and validate a PSCAD simulation model of battery energy storage integration at the DC-link of a wind power system.

The research is focused on the following specific objectives.

- Design and analysis of simulation model of a PMSG-based wind power system using PSCAD software.
- Integration of battery energy storage system at the DC-link of the wind turbine using a DC-DC buck-boost converter.
- Multi-source converter control scheme for power management and DC-link voltage control.
- System analysis of simulation model at different grid power setpoints by introducing time series wind data.
- Control structure to shift the control of DC-link depending upon the state of charge of the battery energy storage system.
- To investigate the enhancement of LVRT capability and improvements in the performance during dynamics of a type-IV PMSG wind turbine by integrating a battery energy storage system.

1.4 Dissertation Outline

The dissertation is organized as follows:

Chapter 1 Provides the introduction and motivation for choosing the research topic. Also mentioned are the key research objectives to achieve.

In Chapter 2, A literature review and basic concepts are presented. In addition, a general overview of wind turbine trends, industrial revolution, wind energy growth, grid integration issues, the basics of wind energy concept, challenges in wind power integration, and energy storage systems advancement for future power system growth

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are discussed.

In Chapter 3, Battery energy storage system integration for wind power systems, wind turbine different types conceptual design and their properties and applications are discussed. In addition PMSG-based wind turbine consideration for battery energy storage integrated wind power system concept explained and because of which properties battery energy storage is preferred over different types of energy storage technologies. And at the end, the proposed system configuration is presented.

In Chapter 4, The general framework of the battery energy storage integrated wind power system implementation design and control methodology is discussed. Also mentioned the Multi-source converter control scheme for DC-link integrated BESS for Power management (Peak shaving).

Chapter 5 Describes the simulations and results of type-4 wind turbine model at different wind speeds as well as time series wind data and grid power setpoints are discussed and the results are presented to analyze the BESS response to stabilize power requirements for various case scenarios to achieve peak shaving. In the end SOC permit control of BESS has also been discussed

Chapter 6, Focuses on enhancing the grid integration of large wind farms, particularly in dynamic environments, by integrating a battery energy storage system into wind turbine architecture to achieve better LVRT capability in case of dynamics in power systems. Presents a case study using a battery system during grid faults dynamics. The simulation results demonstrate the battery feasibility and LVRT effectiveness of the projected topology and control strategy to overcome power curtailment issue during DC link overshoot scenario .

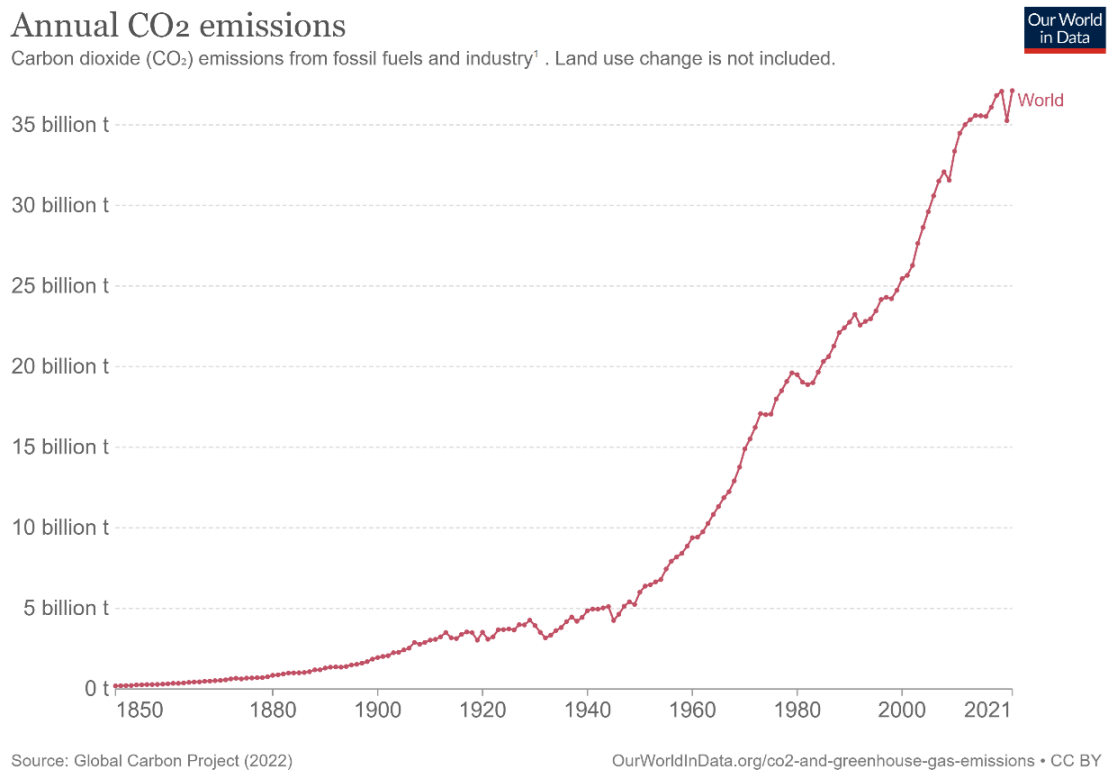
The main conclusions drawn from this dissertation are described in Chapter 7 together with some perspectives and recommendations for future work.

2 Literature Review

This chapter includes the background and basic concepts about wind power production's importance and advancement in the renewable power sector through new technologies participation through storage. As the world population is continually rising and energy demand increases accordingly, Renewable Energy Sources (RES) pose a great solution for achieving these goals. The abundance of solar, wind, hydro, and biomass ensures a continuous supply of clean energy for generating electricity. Moreover, the advancement of renewable energy research made possible by technological breakthroughs has made renewable technologies cheaper and far more ubiquitous than they were in previous years. Nowadays, distributed power systems are gaining great attention due to the advantages of being more reliable, easily scalable, and flexibly controlled than large centralized power systems [10]. The microgrid is emerging as a potential concept for realizing this distributed power system paradigm. The integration of renewable energy sources (RES), energy storage systems (ESS), and dynamic loads makes it possible for microgrids to operate in grid-connected mode and exchange power with the main utility, or in islanded/stand-alone mode to supply local loads when the grid is not present. Many renewable energy technologies can be deployed at various scales, from small individual units to large wind farms. This flexibility allows for tailored energy solutions that can meet the needs of different regions. Renewable energy systems, especially when combined with energy storage, offer more decentralized energy production [11]. This reduces the risk of large-scale power outages and enhances the resilience of energy systems against natural disasters or geopolitical disruptions. BESS plays a vital role in frequency regulation, voltage support, and peak shaving, making them essential for integrating large-scale wind energy into the grid. The integration of BESS with wind farms enhances the reliability and flexibility of the power system. The integration of smart grid technologies with wind energy and BESS is crucial for optimizing energy management. Advanced control systems, predictive analytics, and machine learning are being explored to enhance grid resilience and reliability. The integration of wind energy and battery energy storage systems is pivotal for the future of sustainable energy. While significant progress has been made, ongoing research and development are essential to overcome current challenges and fully realize the potential of these technologies.

2.1 Industrial Revolution

Electricity generation is one of the largest industry globally. Electricity emerged as a revolutionary energy source during the latter part of the 19th century, contributing to the industrial revolution. The introduction of electricity during the industrial revolution not only transformed industries and infrastructure but also laid the foundation for modern technological development. It democratized access to energy, enabling a wide array of innovations that fueled the continued expansion of economies well into the 20th century. Electrical generation from fossil fuels (coal, oil, gas), is the main contributor of CO₂ emissions in the world as shown in figure 2.1[12].



1. **Fossil emissions:** Fossil emissions measure the quantity of carbon dioxide (CO₂) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO₂ includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.

Figure 2.1: Annual CO₂ emissions

CO2 emissions are the main reason for the rise in global temperatures. Global warming (climate change) concerns, (drought, extreme temperatures, forest fires, storms, floods). The irregularity in global temperature has been shown in figure 2.2

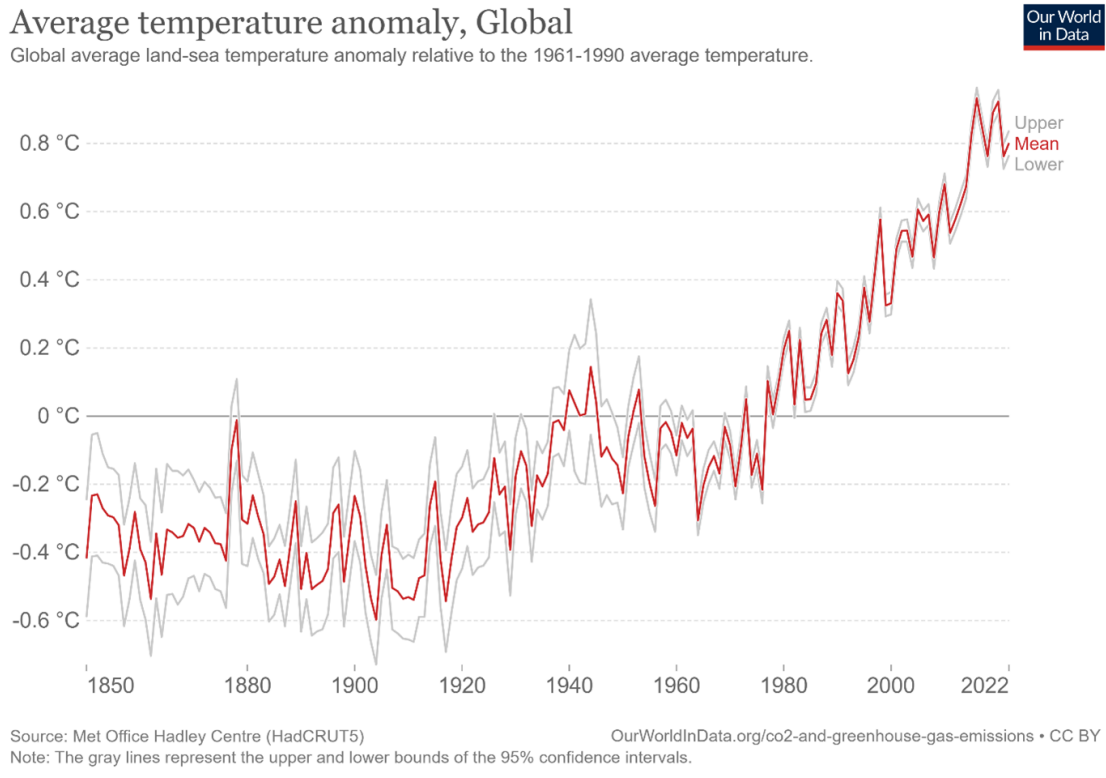


Figure 2.2: Average global temperature irregularity

2.2 Wind Energy Growth

Wind energy has experienced significant growth over the past few decades, driven by technological advancements, decreasing costs, and the global shift toward renewable energy sources. The installed wind energy capacity has been steadily rising as nations and regions all over the world realize how important it is to switch to renewable energy sources. The construction of bigger wind farms with more powerful turbines has been made possible by technological improvements and economies of scale. To address climate change concerns the trend has shifted towards renewable energies, environment-friendly, cost-effective, and sustainable. The adoption of renewable energies by European countries is quite remarkable, especially by Germany [13].

2 Literature Review

The gross power production through different power sources has been illustrated in figure 2.3, where a rapid increase in renewable power sources can be visualized.

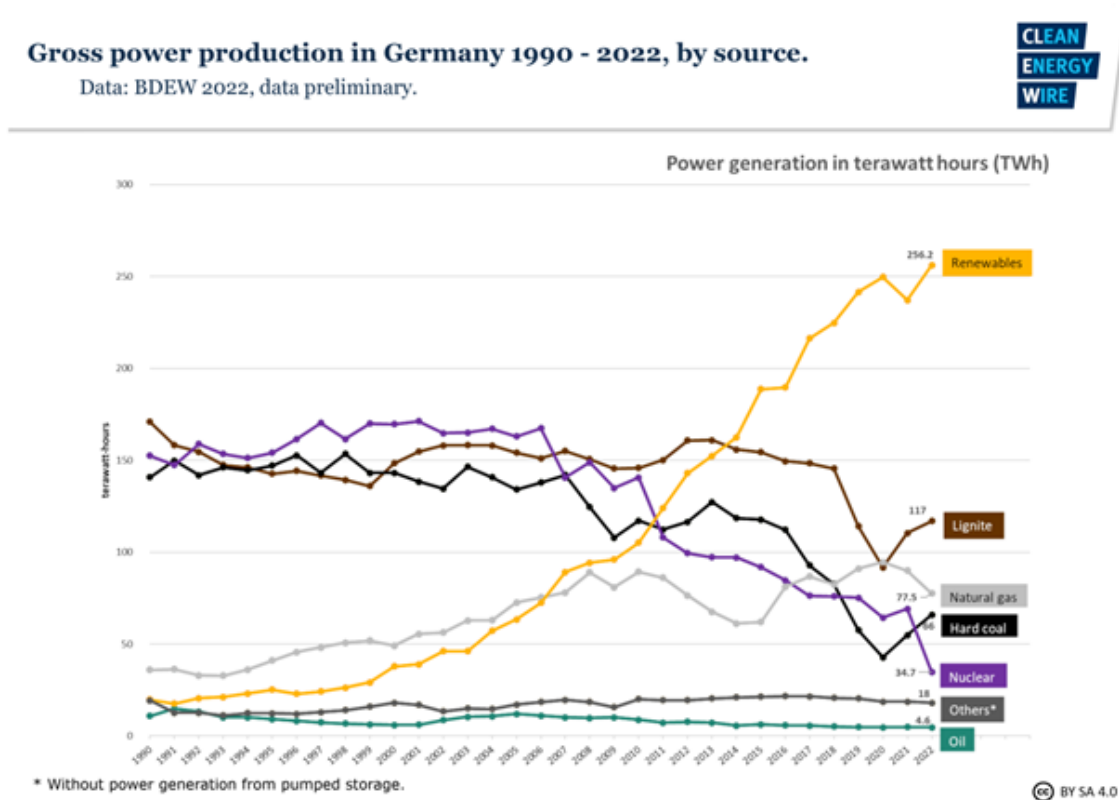


Figure 2.3: Gross power production in Germany 1990-2022

Wind power generation has emerged in terms of installed capacity, Significant technological advancements in wind turbine size, generators, power electronics converters, and predictive maintenance. Gross electricity production from onshore and offshore wind energy in 2022 was 123.45 TWh. wind power has almost 23 percent net share in the German electricity production [14]. The development of wind power production in Germany is presented in figure 2.4

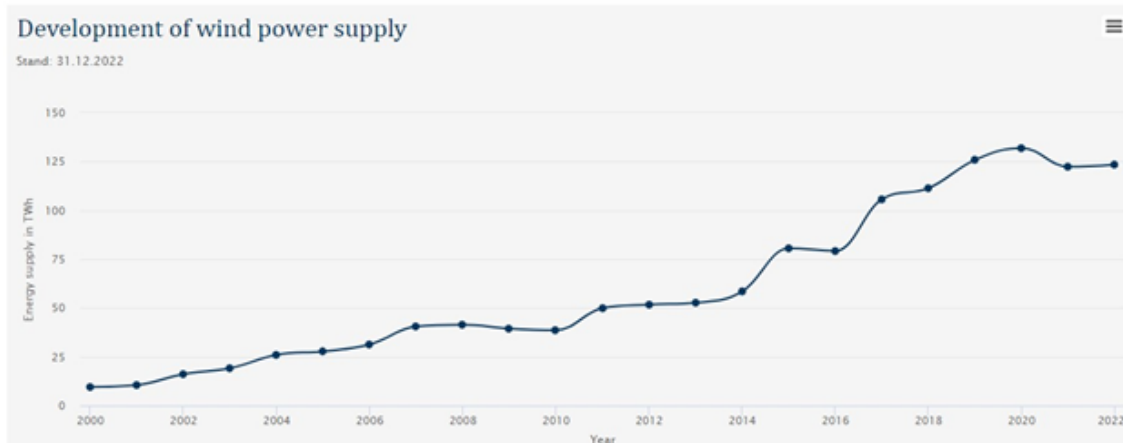


Figure 2.4: Gross wind energy production in Germany over years

2.3 Renewable Energy Penetration Challenges

In electrical power systems, renewable energy penetration presents several challenges that must be addressed to achieve a sustainable and reliable energy system. These challenges include technical, economic, and regulatory issues. Renewable energy sources like wind and solar are intermittent and variable, leading to fluctuations in power generation [15].

Wind energy's intermittency presents significant challenges for system operators due to its variable nature. These challenges include time of day, seasonal variations, and sudden changes in wind availability, which can create mismatches between power supply and demand. Since power demand does not decrease when wind energy supply drops, operators must manage these shortages effectively. Wind availability often does not align with the specific timing of power needs, complicating the integration of wind energy into the grid. At lower levels of renewable energy penetration, these intermittency issues are not particularly unique. Grid operators are accustomed to dealing with breakdowns in conventional power generation and fluctuations in power demand. They have established several strategies to address these challenges. Power systems are typically vast networks that rely on multiple sources of power generation and deliver electricity to a wide range of users. This involves large-scale transmission of electricity to key nodes and its subsequent distribution to users, which include everything from large industrial complexes to individual households. These systems are meticulously designed and carefully planned.

The challenge of maintaining such a system is heightened by the fact that electricity flows almost instantaneously, with limited options for storage. Therefore, any

disruptions in the system such as power plants or industrial users going offline or transmission line failures must be corrected within seconds. Additionally, like all mechanical systems, power plants require periodic maintenance, necessitating the availability of reserve power during these times [16].

High penetration of renewables can affect grid stability, causing frequency and voltage fluctuations. Renewable energy sources can introduce power quality issues like harmonics, flicker, and transient stability problems [17]. At times of low demand and high renewable generation, excess energy may need to be curtailed, leading to wastage. Insufficient support for research and development can slow down technological advancements in renewable energy and associated technologies [18].

2.4 Potential Solution Through Energy Storage Technologies

The growing integration of intermittent renewable energy sources is introducing new challenges to the stability and reliability of power systems. Various solutions exist to address the challenges of integrating variable energy into the power grid, such as expanding and strengthening the grid, improving production forecasts, implementing demand response, utilizing flexible generation sources, and incorporating energy storage. While flexible generation sources like gas turbines and hydroelectric power, as well as grid expansion, may require substantial capital investment, demand response, and better forecasting can enhance the grid's flexibility but do not fully address power quality and stability issues associated with high penetration of variable renewable energy (VRE). Traditional generators, typically designed to operate at constant output levels, are not well-suited to provide the quick flexibility needed in modern grids with significant renewable energy. Energy storage, by decoupling supply and demand and allowing for momentary shifts, is seen as a solution to intermittent production, helping to reduce voltage fluctuations, increase system flexibility, and enable the storage and dispatch of renewable energy [19].

Electrochemical battery energy storage systems present a promising solution to these issues by allowing excess renewable energy to be stored and released when necessary. Battery Energy Storage Systems (BESS) play a critical role in addressing the challenges associated with high renewable energy penetration. By providing energy storage, grid balancing, and ancillary services, BESS enables a more stable, flexible, and resilient power system that can accommodate the growing share of renewable energy [20]. BESS can store excess renewable energy during periods of overgeneration and release it during times of high demand, effectively shifting load

2.5 Grid Integration Issues Overcoming Through BESS

and smoothing out supply-demand imbalances. This reduces the need for curtailment and enhances the overall utilization of renewable energy. By storing energy when renewables are generating and discharging when they are not, BESS can firm up the capacity of renewable resources, making them more reliable and capable of meeting peak demand. BESS can be strategically deployed to alleviate congestion and support grid infrastructure, potentially deferring or reducing the need for expensive upgrades to transmission and distribution networks. This can make the grid more flexible and resilient to the variability of renewable energy [21, 22].

2.5 Grid Integration Issues Overcoming Through BESS

It is difficult to integrate a significant quantity of wind energy into the existing electrical grids. The amount of energy produced by wind is erratic and varies with shifting wind speeds [23]. To ensure a reliable and predictable power supply, grid operators must incorporate energy storage technologies. The crucial role of energy storage technologies, such as batteries and pumped-storage hydroelectricity, has been highlighted by the rise of wind energy. By storing surplus energy generated during windy periods and releasing it during periods of low wind activity, these storage systems improve grid stability and maximize the use of wind resources. The energy transition requires solutions to store the energy from solar and wind power production decentrally and to balance out fluctuating production capacities. Centralized solutions such as pumped storage power plants require a lot of space and capital - the easiest way would be to store the electricity decentrally in batteries. The focus is increasingly on the innovative BESS, which stores electrical energy during the off-peak period and releases it during the on-peak period [24]. This almost unlimited scalability makes BESS ideal for grid storage for the energy transition. For the implementation of BESS solution towards the renewable power sector, there are some critical challenges that should be kept in mind and goals should be achieved to implement storage solutions. Below is a table that presents a comprehensive view of the challenges associated with BESS integration and the corresponding goals to overcome these hurdles, enabling a more effective and widespread adoption of energy storage solutions in the power grid.

2.6 Challenges Of Battery Energy Storage System (BESS) Integration Into Power Grids

The integration of Battery Energy Storage Systems (BESS) into power grids presents various challenges, despite the numerous benefits they offer for energy storage, grid stabilization, and renewable energy integration [25]. Here's an overview of the key challenges and the goals of potential solutions presented in Table 2.1.

Despite the numerous challenges associated with the integration of BESS into the power grid, solutions focused on cost reduction, technology advancements, and regulatory improvements are key to overcoming these obstacles. By addressing these challenges, BESS can play a crucial role in enhancing grid stability, integrating renewable energy sources, and supporting the transition to a low-carbon, sustainable energy future.

2.6 Challenges Of Battery Energy Storage System (BESS) Integration Into Power Grids

Table 2.1: Challenges of BESS integration into the power grid and solution goals

Challenge	Description	Solution Goals
High Initial Costs	The upfront capital costs for BESS, including batteries, inverters, and installation, are high, making economic justification challenging	Reduce costs through economies of scale, technological advancements, and financial incentives
Battery Degradation	Batteries degrade over time, losing capacity and efficiency, leading to reduced performance and the need for replacements	Improve battery lifespan through advanced materials and better management systems
Regulatory and Policy Barriers	Existing regulations may not fully support or incentivize BESS deployment, leading to uncertainties in revenue and market participation	Advocate for updated regulations and policies that recognize and support the value of BESS
Operational Complexity	Optimizing BESS operation within the grid requires sophisticated software and coordination with other grid resources	Implementing advanced energy management systems and AI-based optimization tools for efficient operation
Space Requirements	BESS installations require significant space, particularly for large-scale systems, which can be a constraint in certain locations	Innovate higher energy density batteries and explore modular, space-efficient designs
Environmental and Safety Concerns	Concerns about battery recycling, disposal, and the risk of fires or explosions pose environmental and safety challenges	Enhance safety standards, improve recycling processes, and develop safer battery chemistries
Technological and Performance Limitations	Current battery technologies have limitations in energy density, charge/discharge cycles, and efficiency, impacting overall performance	Invest in Research and Development to develop modern batteries with high performance, low degradation

2.7 Energy Storage Technologies Considerations

The efficient choice of energy storage for any system requirements depend upon

- How long the energy need to be stored for
- Reliability
- The magnitude of energy that needs to be stored.
- The energy demand vs power rating profile
- The life expectancy of the storage required;

There are different ways to store energy that may be suitable for the required conditions. Among all of them, Battery energy storage is at top of the list for power transmission and distribution and grid support as shown in figure 2.5[26][27]

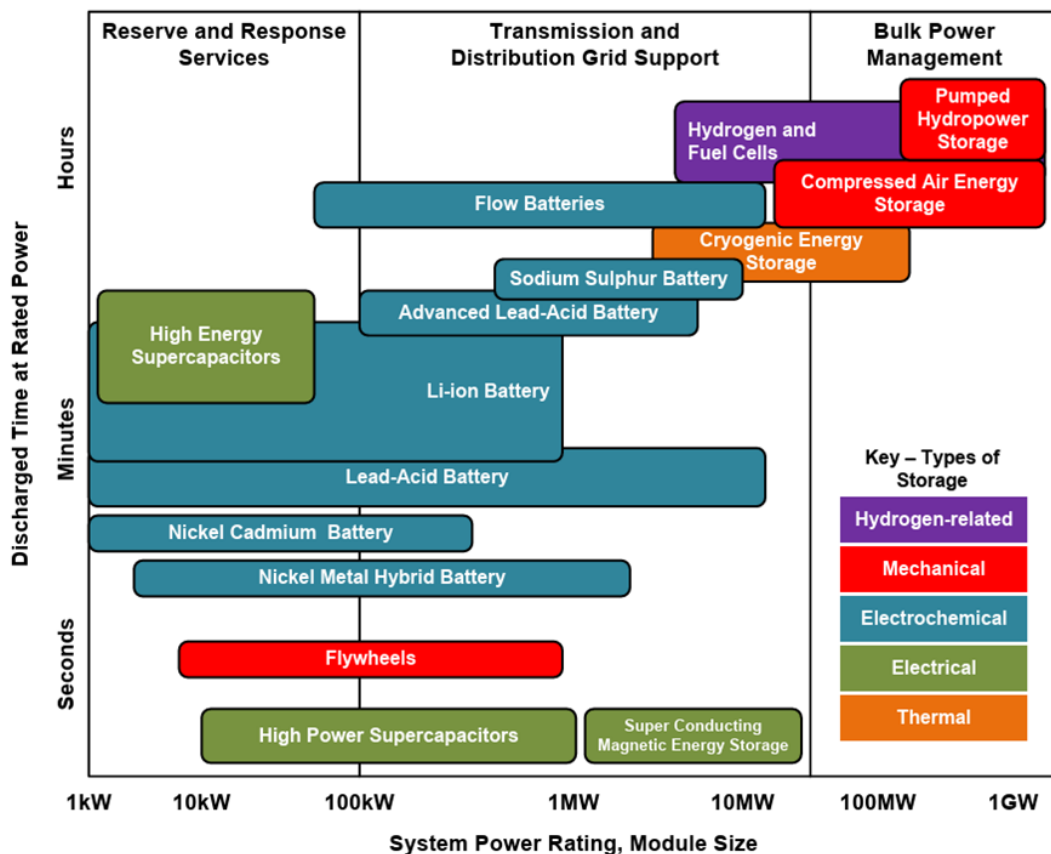


Figure 2.5: Different energy storage technologies according to system power ratings and discharge power duration

2.8 Wind Energy Future Through Battery Energy Storage System Advancement

The integration of renewable energy sources, particularly wind power, into the modern electricity grid marks a pivotal step toward a sustainable and environmentally responsible energy future. Wind power plants tap into the kinetic energy of the wind to generate electricity, offering a clean and renewable energy source. However, the intermittent nature of wind power generation poses unique challenges to grid stability and reliability.

The long-term unpredictability and fluctuating nature of renewable energy sources like wind and solar make a certain amount of energy storage necessary. Battery storage in combination with wind turbines has been explored and developed recently by several research institutes and companies [28]. Besides storage, the stabilization of the electrical grid is an issue and an active field of research and development. So-called ancillary services are needed to keep the grid stable. These services have been provided so far by the power plants where synchronous generators are directly connected to the grid. In the future with higher penetration of renewable the ancillary services have to be provided by wind turbines, PV power plants, and other generation methods. The intermittent and fluctuating nature of renewable energies in general, and wind energy in particular, is one of the major difficulties in integrating them with a high percentage in electricity generation, as this can be prejudicial to the electrical grid stability. The first step in finding solutions to overcome this drawback is to better model and understand the effect of wind variations on the performance of the entire wind turbine system. Once a reliable model is achieved, one can use it to study and optimize technologies that can potentially help solve the problem. The development of such a model would be in itself an important scientific result and would allow the research and development partners to upgrade the national capacity in the field. The second step is to introduce technologies capable of bringing a solution i.e. in the present case the grid stabilizing generator, converter, and integrated battery storage. For economical reasons, the solution feasibility has to be tested and its parameters optimized using the developed model.

Battery Energy Storage Systems (BESS), characterized by versatility and rapid deployability, provide a solution to mitigate the variability of wind power. When strategically integrated into the energy system, BESS can store surplus energy during periods of high wind generation and release it during peak demand or low wind conditions, contributing significantly to grid stability. This approach seeks to maximize the absorption of renewable energy [29] Wind power generation systems are increasingly focused as autonomous power sources in remote and isolated locations. The

2 Literature Review

global annual growth rates for grid-connected wind power generation have been remarkable in recent years. This surge in wind-based electrical power systems can be attributed to their enhanced efficiency, security, and cost-effectiveness as renewable energy sources. They also offer superior control over both active and reactive power generation compared to traditional fossil fuel and nuclear energy systems. The goal in upcoming years is to fulfill the same level of overall electric power demand, with lesser fossil fuel, nuclear power, and similar resources while relying more on wind and solar green energy resources, the electricity generation 2050 forecast is presented in figure 2.6[30]. Consequently, there is an urgent need for comprehensive analysis and research in the field of wind energy especially in the field of storage technologies.

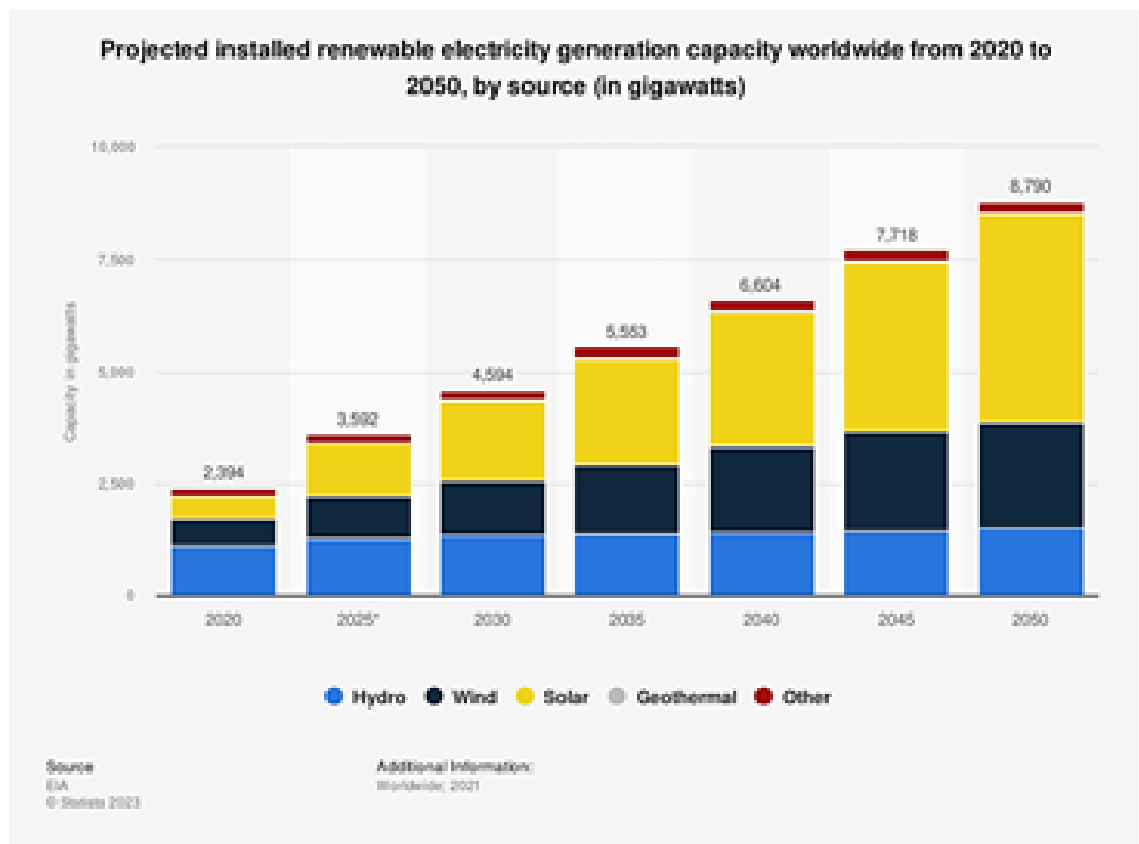


Figure 2.6: Renewable energy generation forecast 2050

The unstable nature of the current supplied to the grid by traditional renewable energy sources can cause distortion in the load voltage and current to the grid. The inclusion of battery systems in wind power systems helps to stabilize the supply of power to the grid and minimize voltage distortion. The benefits of combining BESS with renewable energy projects are emerging nowadays numerously. The largest risk

2.8 Wind Energy Future Through Battery Energy Storage System Advancement

is connecting the BESS to the control center; however, these risks are well-understood by both developers and researchers and hence easily managed.

The requirements for renewable electricity generators need to be extended in the future to cover all necessary ancillary services. These issues will be tackled in this research by using a wind turbine with energy storage as an integral part of the power generation system. An innovative new type of converter system for a wind turbine that consists of a multi-source grid-side converter, an integrated battery storage, and power management system that is specially designed for grid stabilization. It is critical to incorporate proper control, monitoring, and grid interaction mechanisms to maximize the integration of renewables into the electrical grid and overall system stability [31]. In terms of wind power, when production curtailment is anticipated, it will be crucial to develop combined generation/storage solutions. By doing so, the electrical wind power production excess for the network could be stored (for example, by using a Converter and charging a battery with the excess power), and later, the stored power is injected into the system during periods of low wind speeds. For such applications, selecting a battery system needs several aspects to be taken into account,

- Wind Power Generation

The Ampere rating is the factor used to represent the power storage capacity of the battery. The size of the battery is selected based on the power needed to be stored.

- Charge and Discharge Control

Battery unit systems used in wind energy systems are charged and discharged based on the converter control algorithm. To ensure a proper lifetime operation of the battery management system the converter may employ advanced charging systems like trickle charging and cell balancing.

- Grid Interaction

For grid-connected systems, the wind farm's intermediate nature is partly handled by the grid source. Therefore the role of the battery in this case is one as a reserve unit. This makes the size of the storage battery small. The same scenario is found in batteries used in voltage mitigations, where the faults are transient in nature. The quick response time of the battery-based converter is the main reason for its success as a compensator.

2 Literature Review

- SOC Charge Range

The time shift is mathematically described by the relationship involving the SOC, assuming that demand (P_{dem}) is known ahead of time (as a day ahead of market demand). The BESS must have enough energy to operate during peak hours. Thus, the nominal capacity of storage is specified as E_{BESS} , the state of charge range is SoC_{ts} , and the battery's minimum SOC at the end of the application is SoC_{min} . The following is the relationship found in the equation

$$SoC_{ts} = \frac{P_{dem}}{E_{bess}} + SoC_{min} \quad (2.1)$$

The total power to be supplied by the wind energy farm, to the grid (P_{renew}) is given in the equation

$$P_{renew} = \sum_{k=1}^n P_k + P_{st} \quad (2.2)$$

where

P_k is the power produced by the k th generator

P_{st} is the Power supplied by the battery storage system

n is the number of turbine units

For equation 2.2 in discharging mode $P_{st} > P_{min}$, is the constraint for the battery unit to supply the power grid. Similarly, the converters operate in charging mode when $P_{st} < P_{min}$. The value of P_{min} depends on the type of the battery used.

2.8 Wind Energy Future Through Battery Energy Storage System Advancement

As a result of the extensive survey on the features of wind energy: wind power stability, LVRT in the grid-connected systems, and battery energy storage for renewable, the following gaps are identified.

- Modeling complexity
- Control strategy limitations
- Optimal sizing and placement
- Economic viability
- Multi-objective Operation control structure
- DC link overshoot power curtailment issue

A complete simulation study is needed on the transient behavior of the PMSG with strong and weak grids. MATLAB package was mostly used by researchers working on wind energy. The models of type-IV wind turbines were introduced in the PSCAD 4 and later versions. The rich features of this software can be explored by power systems researchers. For automated studies and for simple switching studies the PSCAD versions can work in coordination with Python for larger bus architectures. Why PSCAD software is preferred is discussed in Table 2.2.

Table 2.2: Why PSCAD is Preferred over MATLAB/Simulink

Aspect	PSCAD	MATLAB/Simulink (SimPowerSystems)
Power System Accuracy	Designed for electromagnetic transient simulations, very accurate for fast transients	Mostly suited for phasor-based and average models EMT simulations require additional toolboxes
Simulation Speed	Optimized for fast EMT simulations with detailed electrical components	EMT simulations are typically slower and need fine tuning of solver settings
Ease of Control	Control logic and power electronics coexist in the same GUI with time-step synchronization	Requires careful synchronization between control (continuous) and power (discrete) domains
Industry Usage	Widely used by utilities, manufacturers, and grid planners for EMT studies	More common in academic and control system design contexts

3 Battery Energy Storage Integrated Wind Power System Conceptual Design

In this chapter, the basics of wind energy systems, different types of wind turbines, battery energy storage systems for wind power systems, their conceptual design, and their properties and applications are discussed.

3.1 Wind Energy Concept

Wind energy exists in the form of kinetic energy due to air movements in the atmosphere. This kinetic energy is generated by various factors such as the uneven heating of the Earth's atmosphere by the sun, inequalities on the Earth's surface, and the Earth's rotation. Wind, as a renewable energy source, can be harnessed to produce electricity.

To convert wind energy into usable electricity, machines and equipment are required. These machines, commonly known as windmills or wind turbines, are designed to capture the kinetic energy present in the wind and convert it into mechanical energy. This mechanical energy can then be further converted into electrical energy using an electrical generator.

The principle working phenomena of a wind turbine architecture are established on the aerodynamic lift convention. A wind turbine extracts the maximum available wind energy from the surrounding environment and converts this into mechanical energy, which is later transformed into electricity at the output terminal. The fundamental elements that make up a wind turbine unit are the rotor, efficient blades, hub, robust tower, anemometer, gearbox mechanism, braking system, generator and controllers, and yaw entity. The extensive details of wind turbine working are presented in [32]. A wind turbine unit relies on wind quality for power generation, and the amount of power a wind turbine unit can generate is highlighted in equation (3.1)

$$\text{Power}_{\text{wind turbine}} = \frac{1}{2} \rho \pi \left(\frac{D}{2} \right)^2 V^3 C_p \quad (3.1)$$

Where ρ is the air density, D is the diameter of the rotor blades, V is the wind speed,

C_p is the power coefficient. C_p depends on tip speed ratio λ of wind turbine and pitch angle β of blades. Wind speed, in correlation with the power curve, is an essential aspect of wind turbine performance that anticipates the rated power generation by a wind turbine unit at various wind speeds.

Over the past several decades, wind energy technology has experienced significant advancements. There has been a considerable amount of research and development aimed at improving various aspects of wind energy production. These efforts focus on optimizing wind turbine design to maximize energy output, reducing costs associated with wind energy generation, and enhancing the reliability and dependability of wind turbines.

Innovation in wind technology continues to progress, with ongoing research aimed at developing the latest concepts and technologies to further improve the efficiency and effectiveness of harnessing wind energy. By investing in research and development, the goal is to make wind energy a more viable and sustainable source of electricity generation for the future [33].

3.2 Wind Turbine Types

Wind power technology uses energy from the wind to convert it into electric energy. Currently, there are four different types of WTs that exist in the market [34].

- Type-1: Induction generator, with typically squirrel cage rotor with fixed resistance
- Type-2: Wound rotor induction generator, with variable rotor resistance
- Type-3: Doubly-fed induction generator
- Type-4: Induction or synchronous generator with full-converter interface

3.2.1 Type-1 Wind Turbine

Type-1 wind turbines (WTs) represent the most basic form of wind turbine technology. In this configuration, an induction generator (IG) is the primary component, directly linked to the grid via a transformer (TR). Mechanically switched capacitor banks (C) are commonly integrated to ensure reactive power compensation. To protect the system in the event of a fault, both the generator and capacitor banks are disconnected from the grid through the main circuit breaker (CB).

One key characteristic of Type-1 WT is their fixed rotor speed. Unlike other types of wind turbines, the rotational speed of the generator remains constant, regardless of the wind speed. Instead of being influenced by wind speed, the rotor speed is determined by the synchronous speed, which is based on the frequency of the grid power supply.

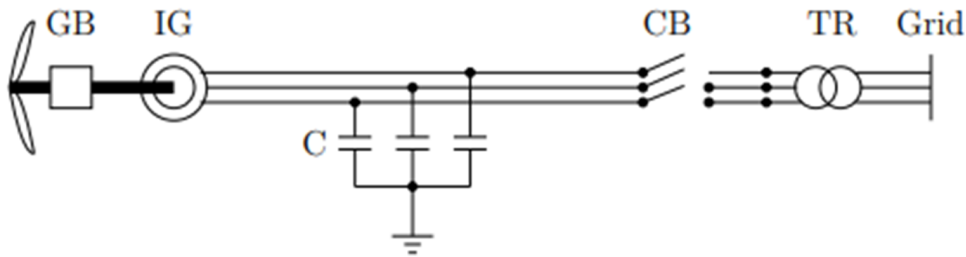


Figure 3.1: Model of Type-1 wind turbine

3.2.2 Type-2 Wind Turbine

Type-2 wind turbines (WTs) share similarities with Type-1 turbines in that they are directly connected to the grid. However, they employ a different type of generator. In Type-2 WT, a wound rotor induction generator (WRIG) is utilized instead of an induction generator (IG).

The WRIG features slip rings connected to the rotor winding. These slip rings enable the implementation of a variable rotor resistance (VRR) system. Through power electronic devices, the resistance in the rotor circuit can be controlled, allowing for adjustments in the generator's characteristics. This control over rotor resistance provides flexibility in managing the turbine's operation and optimizing its performance under varying wind conditions.

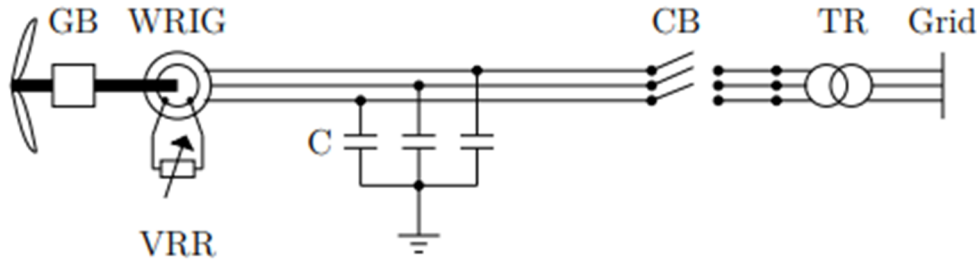


Figure 3.2: Model of Type-2 wind turbine

3.2.3 Type-3 Wind Turbine

Type-3 wind turbines (WTs) employ Doubly-fed induction generators (DFIGs) as their primary generator technology. Unlike Type-1 and Type-2 turbines, where the generator is directly connected to the grid, in Type-3 WTs, the rotor windings of the DFIG are not directly linked to the grid. Instead, an AC-DC and DC-AC converter, known as the grid-side converter (GSC) and machine-side converter (MSC) respectively, are utilized to facilitate the connection between the rotor and the grid.

In Type-3 WTs, the stator windings are directly connected to the grid. The MSC plays a crucial role in regulating both active and reactive power by adjusting the rotor position. On the other hand, the GSC ensures stable voltage levels across the DC-link.

The DC-link serves as a temporary energy storage system primarily for switching events. It is typically small in size and is not intended to absorb excess energy from the machine side or inject energy into the grid side to restore voltage levels. Instead, its main purpose is to ensure smooth operation and stability of the conversion process between AC and DC currents.

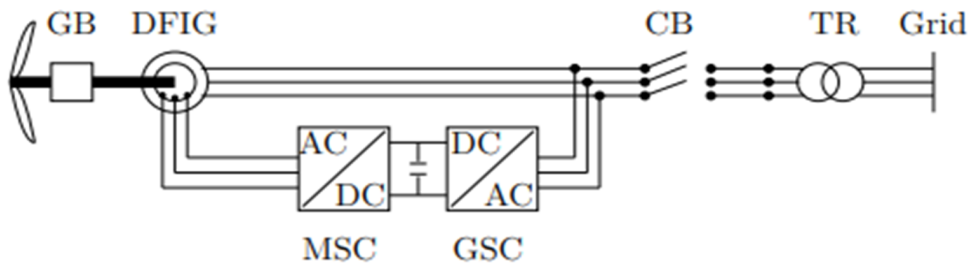


Figure 3.3: Model of Type-3 wind turbine

3.2.4 Type-4 Wind Turbine

The Type-4 wind turbine represents the most advanced and complex technology in wind power generation. It consists of a generator, which can either be an induction generator (IG) or a synchronous generator (SG), connected to the grid via a full-converter system.

Unlike Type-3 turbines, which utilize DFIGs and have only partial decoupling from the grid, Type-4 turbines are fully decoupled from the grid. This enables them to offer better low-voltage ride-through capabilities, ensuring stable operation even during grid voltage fluctuations. However, this increased decoupling comes with higher losses, as all the current passes through the converter. Consequently, Type-4 turbines require higher-rated components, leading to higher switching and conduction losses.

In a Type-4 wind turbine, the machine-side converter (MSC) is responsible for adjusting the rotational speed, while the grid-side converter (GSC) focuses on reducing reactive power consumption and transmitting active power to the grid.

In terms of generator technology, both wound-rotor and permanent magnet synchronous generators (PMSG) can be implemented in Type-4 turbines. However, PMSGs are more commonly used due to their self-excitation capability, resulting in high power factor and efficiency. Additionally, PMSGs allow for direct-driven wind turbines, eliminating the need for a gearbox. This not only increases operational reliability by removing a maintenance-intensive component but also improves overall efficiency [35]. Due to these properties, Type-4 wind turbines are preferable for DC-link interfaced multi-source power systems and storage applications. That's why in this research, Type-4 wind turbine has been used with BESS which is going to be explained in detail in later sections.

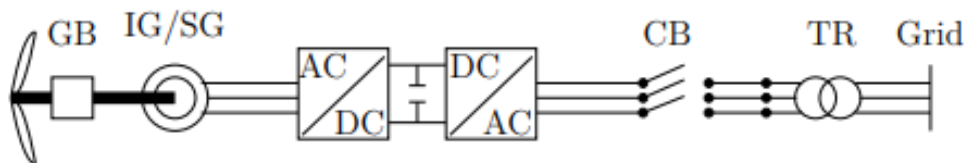


Figure 3.4: Model of Type-4 wind turbine

Table 3.1: Four different types of wind turbine generator schemes key features and their usage

Feature	Type1 Wind Turbine	Type2 Wind Turbine	Type3 Wind Turbine	Type4 Wind Turbine
Generator Type	Squirrel Cage Induction Generator (SCIG)	Wound Rotor Induction Generator (WRIG)	Doubly Fed Induction Generator (DFIG)	Full Converter-based Synchronous Generator (FCSG) or Permanent Magnet Synchronous Generator (PMSG)
Control Strategy	Fixed-speed operation	Limited variable-speed operation via rotor resistance control	Variable-speed operation with partial power electronics	Fully variable-speed operation with full power electronics
Grid Connection	Directly connected to the grid	Directly connected to the grid with controlled rotor resistance	Connected via a partial-scale power converter	Fully decoupled from the grid via a full-scale power converter
Power Quality Control	Limited control over reactive power	Some control over reactive power through rotor resistance	Good control over reactive and active power	Excellent control over reactive and active power
Advantages	Simple, robust, cost-effective	Improved grid compliance and partial speed control	High efficiency, good grid integration, lower power electronics cost	Maximum flexibility, full grid interaction control, optimal efficiency
Disadvantages	Limited to constant speed, no reactive power control	Limited speed range, complex rotor resistance control	Higher complexity, sensitivity to grid disturbances	High cost, complex design, fully reliant on power electronics
Typical Use Case	Older wind farms, cost-sensitive installations	Early-stage variable speed turbines	Modern wind farms, medium to high wind sites	Advanced wind farms, offshore installations, regions with strict grid codes

3.3 Permanent Magnet Synchronous Generator (PMSG) For Wind Turbine

PMSGs use permanent magnets made from rare-earth materials to create the magnetic field, eliminating the need for external excitation. Permanent Magnet Synchronous Generators (PMSG) offer several significant advantages for wind energy conversion systems (WECS), particularly in the context of direct-drive configurations. PMSGs operate efficiently at low rotational speeds, which allows for the elimination of gear-boxes in wind turbine designs. This omission leads to lower overall system costs, reduced maintenance requirements, and increased reliability [36]. The use of permanent magnets provides high torque density and eliminates excitation losses, contributing to the overall efficiency and compactness of the generator. The robust design, high efficiency, and low maintenance requirements of PMSGs make them particularly well-suited for offshore wind turbines, where maintenance access is limited and reliability is crucial. Permanent Magnet Synchronous Generators are a key technology in modern wind turbine design, offering numerous benefits such as high efficiency, reliability, and the capability for direct drive systems. While there are challenges such as cost and the need for advanced control systems, ongoing advancements continue to enhance the performance and feasibility of PMSGs in the wind energy sector [37].

To simulate and control a Permanent Magnet Synchronous Generator (PMSG), a mathematical model in the dq reference frame is commonly used [38]. This model simplifies the analysis and control of the system compared to the real three-phase ABC frame. The DQ reference frame transforms the three-phase sinusoidal quantities into two-phase DC quantities under steady-state conditions. This transformation simplifies the analysis and control of the PMSG [39]. The mathematical model of a PMSG is given as

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \quad (3.2)$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \lambda_m \quad (3.3)$$

Explanation of Terms

- v_d : d -axis component of the stator voltage.
- v_q : q -axis component of the stator voltage.
- i_d : d -axis component of the stator current.

- i_q : q -axis component of the stator current.
- R_s : Stator winding resistance.
- L_d : d -axis inductance.
- L_q : q -axis inductance.
- ω : Electrical angular velocity of the rotor (rad/s).
- λ_m : Flux linkage due to the permanent magnets.

3.4 Energy Storage Systems

Energy storage systems play a crucial role in maximizing the efficiency and reliability of wind energy generation. As wind turbines harness the kinetic energy of the wind and convert it into electricity, they often produce more energy than is immediately consumed. During periods of high wind production, this surplus energy can be stored in energy storage systems for later use.

Energy storage systems serve as a bridge, storing excess electricity and making it available when needed, such as during calm periods when wind production is limited, at night when demand is lower, or even during power outages. By storing and intelligently managing this surplus energy, energy storage systems help ensure a consistent and reliable power supply, thereby maximizing the benefits of wind energy [40]. Energy storage systems (ESS) technologies are becoming of paramount importance due to the smart grid(Automatic control).

The integration of energy storage systems with wind power not only enhances grid stability and reliability but also enables greater flexibility in managing fluctuations in supply and demand. Additionally, energy storage systems contribute to the overall efficiency of wind energy generation by enabling the capture and utilization of excess energy that would otherwise be wasted.

Overall, energy storage systems play a vital role in complementing wind energy generation, helping to overcome its inherent intermittency and variability, and ultimately contributing to a more sustainable and resilient energy system [41]. The primary function of energy storage systems for wind turbines is indeed to capture and store excess electricity, ensuring its availability for later use. These systems commonly utilize advanced battery technologies, with lithium-ion batteries being a prominent example, due to their efficiency and reliability.

During periods of high wind production, when the wind turbines generate more electricity than is immediately required, the excess power is directed towards charging

3.5 Types Of Energy Storage Systems For Wind Turbines

the batteries within the energy storage system. The batteries store this energy in a stable and reliable manner until it is needed.

When electricity demand exceeds the current wind turbine output, or during periods of low wind, the stored energy in the batteries is discharged. This provides a consistent and reliable power source that supplements the electricity production from the wind turbines, ensuring a steady supply of energy to meet demand.

By effectively capturing and storing excess electricity and then discharging it when needed, energy storage systems enhance the overall efficiency and reliability of wind energy generation. They contribute to a more stable and resilient energy supply, helping to mitigate the intermittency and variability inherent in wind power generation.

3.5 Types Of Energy Storage Systems For Wind Turbines

There are several types of energy storage systems for wind turbines, each with its unique characteristics and benefits [41].

3.5.1 Battery Energy Storage System

- Efficiently stores surplus electricity in batteries for future use.
- Offers flexibility and scalability for residential and commercial applications.
- Fast response times, high round-trip efficiency, and on-demand energy discharge ensure reliable power supply

3.5.2 Pumped Hydro Storage

- Utilizes surplus electricity to pump water from a lower reservoir to a higher reservoir, storing energy.
- Releases stored water on demand, flowing through turbines to generate electricity.

3.5.3 Compressed Air Energy Storage

- Stores energy by compressing air and storing it in underground caverns.
- Releases compressed air to propel turbines and generate power when needed.

3.5.4 Flywheel Energy Storage

- Stores energy by rotating a rotor at high speeds, converting excess electricity into kinetic energy.
- Retrieves stored energy by decelerating the rotor, converting kinetic energy back into electrical energy.

While each energy storage system has its unique advantages and applications, **Battery Energy Storage System (BESS)** stands out as a superior choice for wind turbines due to several compelling reasons:

- **High Efficiency:** Battery storage systems offer high round-trip efficiency, ensuring minimal energy loss during charging and discharging cycles.
- **Fast Response Times:** Batteries can respond quickly to fluctuations in electricity demand, providing instantaneous power when needed.
- **Scalability:** Battery storage solutions can be easily scaled to meet varying energy demands, making them suitable for both residential and commercial applications.
- **Compact Size:** Batteries have a relatively small physical footprint, making them suitable for installations where space is limited.
- **Durability and Long Lifespan:** Modern battery technologies are designed to be robust and durable, with long operational lifespans.
- **Versatility:** Battery storage systems can be used for various applications, including self-consumption optimization, backup power, and peak demand management.

Overall, battery energy storage emerges as the optimal choice for maximizing the benefits of wind energy due to its exceptional efficiency, scalability, reliability, and versatility. While other energy storage technologies have their advantages, battery storage systems offer the most comprehensive solution for storing and utilizing surplus electricity from wind turbines [42].

3.6 Major Advantages Of Energy Storage Systems For Wind Turbines

There are several key benefits of energy storage systems for wind turbines, contributing to grid stability, renewable energy integration, and overall efficiency. Here are some key points for implementing storage technologies in wind power systems.

- **Enhanced Grid Stability**

Energy storage systems help balance supply and demand fluctuations, ensuring a stable and reliable power supply by storing excess energy during periods of high wind production and releasing it during peak demand or low wind conditions.

- **Increased Renewable Energy Penetration**

By storing and later releasing excess energy from wind turbines, energy storage systems facilitate the integration of more wind power into the grid, reducing reliance on fossil fuels and advancing the transition to a clean energy future.

- **Time-Shifting Energy Generation**

Energy storage systems enable the time-shifting of energy generation from wind turbines, storing excess energy when production exceeds demand and releasing it when needed, thus optimizing energy utilization and maximizing economic value.

- **Ancillary Services Provision**

Energy storage systems can provide ancillary services such as frequency regulation, voltage control, and grid black-start capabilities, enhancing grid reliability and performance.

- **Cost Reduction**

Declining costs of energy storage technologies make them increasingly cost-effective for wind turbine installations, helping reduce electricity costs by optimizing wind energy use and avoiding peak-time rates.

- **Improved Grid Flexibility**

Energy storage systems offer rapid response times and fast ramping capabilities, providing flexibility to adjust energy supply in real-time to maintain grid stability and integrate wind energy smoothly.

Overall, energy storage systems play a crucial role in maximizing the benefits of wind energy by addressing intermittency issues, improving grid stability, increasing renewable energy penetration, and enhancing overall grid flexibility and efficiency [43].

3.7 Battery Energy Storage System Interfaced Wind Power System

Batteries store chemical energy in the form of chemically charged substances, which can be converted into electrical energy through a chemical reaction. The process of converting chemical energy into electrical energy involves oxidation and reduction reactions, allowing the flow of electrons from one material (the anode) to another (the cathode). A single battery consists of basic units known as cells. Each cell comprises two electrodes: a positive electrode (anode) and a negative electrode (cathode). A separator, typically made of microporous membrane material such as polyethylene or polypropylene, is placed between the electrodes to prevent direct contact. An electrolytic solution (for wet batteries) or an electrolyte (for dry batteries) is absorbed in the separator, facilitating the flow of ions during the chemical reaction. The typical formulation of a basic cell is shown in figure 3.5, which is based on the description presented in [44].

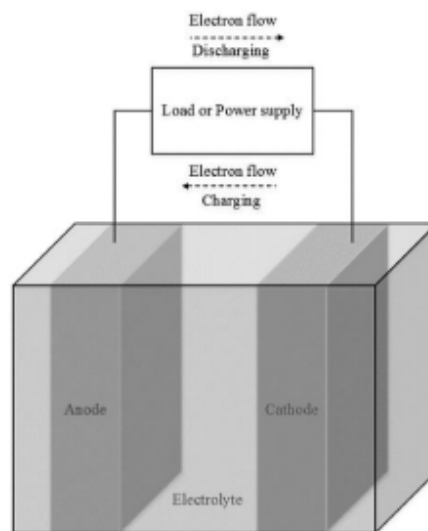


Figure 3.5: A simplified cell diagram

The number of individual cells are connected in series or parallel combinations to assemble a battery module in order to achieve the desired voltage and current levels. Modules are later joined to form a minimum control system for individual cells that can control voltages and currents. Figure 3.6 shows how to construct a

3.7 Battery Energy Storage System Interfaced Wind Power System

complete battery system where several modules are connected in series and parallel with an additional control system such as temperature control, cell balancing, and battery management system

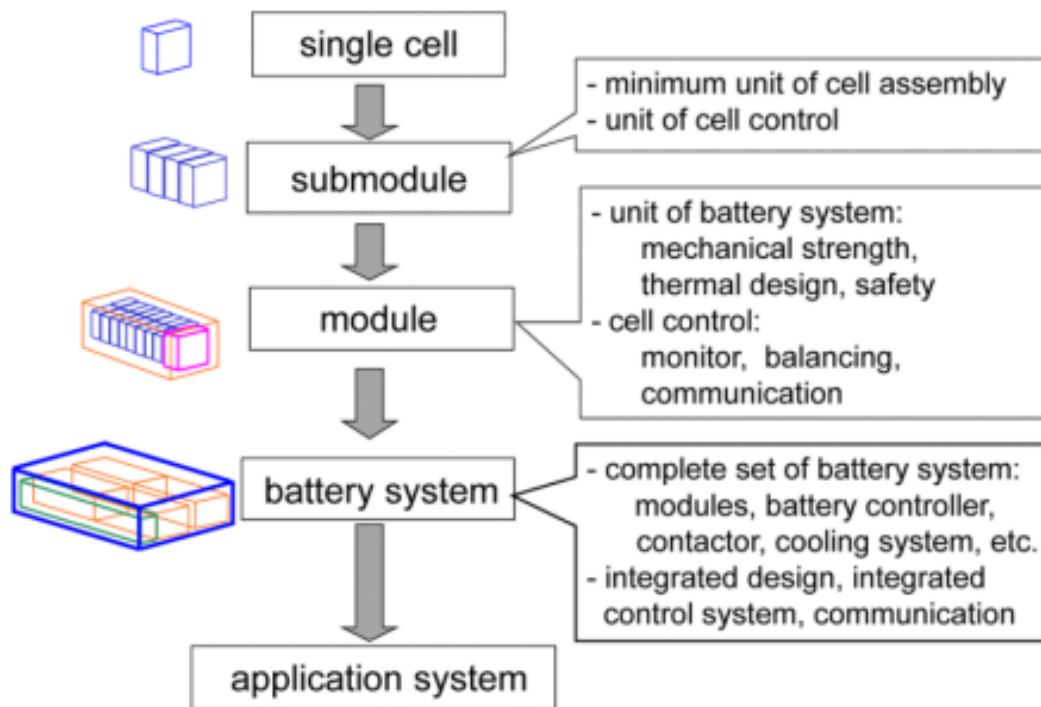


Figure 3.6: BESS Construction

Here's a breakdown of the key points about the diverse scale and capabilities of Battery Energy Storage Systems (BESS)

- **Variety of Applications**

BESS can be deployed for various applications, ranging from small-scale energy storage and management systems for electric cars to large-scale installations for wind farms or photovoltaic systems. They are utilized for smoothing the output of generation and providing grid stability.

- **Wide Range of Sizes**

BESS sizes vary widely, ranging from a few kilowatt-hours to several megawatt-hours. The size of the energy storage system is determined based on specific requirements and duties, such as short-term fluctuation smoothing, frequency regulation, or large-scale power dispatch during power failure events.

- **Modular Design**

BESS modules are parameterized to meet the size and performance requirements of the system. Large-scale BESS typically consists of a large number of moderate-sized cells rather than a few large cells, as manufacturing large cells may not be feasible and can lead to decreased efficiency over time.

- **Short and Long-Term Applications**

BESS can be tailored for both short-term and long-term applications. For short-term applications requiring fast response times and high discharge rates, BESS with low reaction times is preferred. For long-term applications requiring high capacities, larger BESS systems are considered.

- **Fast Response and Efficiency**

BESS can deliver fast and efficient power in emergency situations without long startup times. They can meet grid demands instantaneously and work for extended periods when needed.

- **Installation Time**

The installation of a BESS typically takes a short period of time, up to 12 months, in comparison to other energy storage systems such as pumped hydro, which can take up to 10 years to deploy.

Overall, BESS offers versatility, scalability, and rapid deployment, making it a valuable asset for grid stability, renewable energy integration, and emergency power supply. Their modular design and flexible operation make them suitable for a wide range of applications across various industries.

3.8 Types Of Battery Energy Storage Technologies

Battery energy storage technologies encompass various types of batteries, each with its own characteristics, advantages, and applications. Here are some of the most common types [45]:

3.8.1 Lithium-Ion Batteries

Lithium-ion batteries are widely used in energy storage systems due to their high energy density, long cycle life, and relatively low maintenance requirements. They are utilized in both small-scale applications, such as consumer electronics and electric vehicles, as well as large-scale applications, including grid-level energy storage.

3.8.2 Lead-Acid Batteries

Lead-acid batteries have been used for decades and are still commonly employed in energy storage systems. They are relatively inexpensive and have a proven track record for reliability. However, they have lower energy density and shorter cycle life compared to lithium-ion batteries.

3.8.3 Flow Batteries

Flow batteries store energy in liquid electrolytes contained in external tanks. They can be recharged by replacing the electrolyte solution, allowing for scalability and long cycle life. Flow batteries are suitable for grid-scale applications due to their ability to store large amounts of energy.

3.8.4 Nickel-Cadmium Batteries

Nickel-cadmium batteries have been used for stationary energy storage applications for many years. They offer robustness, high discharge rates, and long cycle life. However, they are less commonly used today due to environmental concerns associated with cadmium.

3.8.5 Sodium-Ion Batteries

Sodium-ion batteries are similar to lithium-ion batteries but use sodium ions instead of lithium ions. They are being researched as a potential alternative to lithium-ion batteries due to the abundance and low cost of sodium. However, they are still in the early stages of development.

3.8.6 Solid-State Batteries

Solid-state batteries use solid electrolytes instead of liquid or gel electrolytes found in traditional batteries. They offer advantages such as higher energy density, improved

3 Battery Energy Storage Integrated Wind Power System Conceptual Design

safety, and longer cycle life. Solid-state batteries are still in the research and development phase but hold promise for future energy storage applications.

These are some of the main types of battery energy storage technologies currently in use or under development. Each type has its own set of advantages and limitations, and the choice of technology depends on factors such as application requirements, cost, and performance characteristics.

Here's a comparison table of different battery storage technologies based on various factors [46] [47]

3.8 Types Of Battery Energy Storage Technologies

Table 3.2: Comparison of different battery storage technologies based on various factors

Factor	Lithium-Ion	Lead-Acid	Flow Batteries	Nickel-Cadmium	Sodium-Ion	Solid-State Batteries
Efficiency	High	Moderate	Moderate	Moderate	Similar to Li-ion	In the early stages of development
Energy Density	High	Moderate	Moderate	Moderate	Similar to Li-ion	Potentially high
Cycle Life	Long	Moderate	Long	Long	Still in research	Expected to be long
Cost	Moderate to High	Relatively Low	Moderate to High	Moderate	Expected to be low	Currently High
Safety	Generally safe	Relatively Safe	Generally Safe	Moderate	Safety TBD	Expected to be safer
Environmental Impact	Low	Moderate	Moderate	Moderate	Lower than Li-ion	Potential for lower

The most common type used today is lithium-ion. The lithium-ion battery is mainly used because of its high efficiency, high energy, and power density, fast charging, and also long life attributes.

3.9 Properties Of Battery Energy Storage Systems

Here are some key properties of battery energy storage systems (BESS):

- **Energy Storage Capacity**

BESS can store electrical energy in the form of chemical energy, which can be discharged when needed. For describing the energy capacity of a battery, the difference between energy and power should be kept in mind. Energy is a quantity that can be transformed from one form to another, whereas power is the rate of change of energy. Batteries are rated either in kilowatt-hour (KWh)/Megawatt hour (MWh) or in Ampere hour (Ah). A battery stores energy in the form of charge and its capacity is measured with the amount of discharge current represented in terms of ampere-hour(Ah) and with a fixed amount of terminal voltage (V), Voltage* Amps * hours = Wh. A battery with an energy capacity of 1MWh with a discharge rate of 1C can deliver 1 MW of power in 1 hour. In most of the batteries, energy capacity and power rating are fixed depending upon their design and requirements.

- **Power Rating**

The power rating of a Battery Energy Storage System (BESS) refers to the maximum rate at which the system can deliver or absorb electrical power. It is typically measured in kilowatts (kW) or megawatts (MW) and is essential for determining the system's ability to meet the power demands of a given application. The power rating of a BESS is a critical parameter that determines its ability to provide reliable and efficient electrical power for various applications, ranging from grid stabilization to renewable energy integration and backup power systems. It is essential to carefully consider the power rating requirements during the design and specification of a BESS to ensure optimal performance and compatibility with the intended application

The power rating of a BESS depends on various factors, including the type and configuration of the batteries used, the design of the power conversion system, and the intended application

- **Discharge Rate**

The discharge rate, also known as C-Rate, is a measurement of discharge current in relation to the battery's total capacity. It indicates how fast a battery can be discharged while keeping all the operating conditions in the account. A battery with 100 Ah capacity will deliver 100 amperes for 1 hour if drained at 1C (discharge rate) Whereas if it is discharged at 0.5C, it will deliver 50 amperes for 2 hours. As with changing the discharge rate battery usage time can be varied according to the requirements. But depending on the type each battery has a specific limitation with C-rate, some battery has the ability such as lead-acid have a discharge rate of 5C, on the other hand, Lithium-ion has a discharge rate of 0.5C to 2C. As the C-Rate decreases, the discharge time increases and the battery can be used for a longer duration

- **Efficiency**

BESS has an efficiency rating that indicates how much of the stored energy can be successfully retrieved during discharge compared to the energy input during charging.

- **Response Time**

BESS can respond rapidly to changes in demand or supply, providing quick injections of power when required.

- **Cycle Life**

BESS has a limited number of charge and discharge cycles before their performance deteriorates significantly.

- **State of Charge (SOC)**

BESS can indicate the amount of stored energy relative to its maximum capacity, allowing users to monitor and manage its usage effectively.

- **Depth of Discharge (DoD)**

Depth of discharge is described as the usable storage capacity of the battery system. DoD is defined as the percentage of a battery that can be discharged as compared to fully charged capacity or to what extent a battery can be discharged without impacting its life cycle. For example, a battery system of 100 kWh capacity with DoD of 80 percent means for practical application 80 kWh should be used for long life operation. The equation 3.4 shows DoD in terms of SOC.

$$\text{DoD} = 100\% - \text{SOC} \quad (3.4)$$

Depth of discharge also depends on the cycle of charging and discharging. If a battery is frequently discharged at a lower percentage such as only 10 percent of its total capacity, then it may have 10,000 cycles as compared to a battery that fully discharges up to 80 percent have 3000 cycles in its life span.

- **Energy and power density**

The measure of energy stored in a given mass or volume is defines as energy density and it is expressed in watt-hours per kilogram (Wh/kg). A battery system with a high energy density can contain a lot of energy in a little amount of area or mass, while also being lightweight and having more capacity . Similarly, power density is the amount of power stored in a particular mass(W/Kg). The difference between power density and energy density is the same as power and energy. It can be explained with an example that batteries have more energy density whereas capacitors have more power density, which means batteries can store more energy, whereas capacitors give off energy more rapidly.In comparison to lead-acid, nickel-cadmium and lithium-ion batteries currently available, lithium-ion offers a greater specific power and energy density.

- **Voltage Range**

BESS operates within a specific voltage range, which determines the conditions under which they can charge and discharge efficiently.

- **Safety Features**

BESS may include safety features such as overcharge protection, over-discharge protection, and thermal management systems to ensure safe operation.

- **Scalability**

BESS can be designed to be scalable, allowing for expansion or contraction of storage capacity based on changing energy needs.

- **Integration with Renewable Energy Sources**

BESS can be integrated with renewable energy sources such as solar or wind power to store excess energy generated during periods of low demand or high generation.

3.9 Properties Of Battery Energy Storage Systems

- **Grid Services**

BESS can provide various grid services such as frequency regulation, voltage support, and peak shaving to enhance grid stability and reliability.

- **Environmental Impact**

BESS may have varying environmental impacts depending on the materials used in their construction and disposal methods. Proper recycling and disposal practices are essential to minimize environmental harm.

These properties determine the performance, reliability, and suitability of battery energy storage systems for different applications and environments [48].

3.10 Proposed BESS Interfaced Wind Power System configuration

The proposed designed system in which a BESS is introduced at the DC-link of the wind turbine simulation model consists of various sub-blocks such as wind side and grid side converter and their control blocks which also include the designed control system for the DC-link voltage and output power control with battery converter and control scheme as shown in figure 3.7

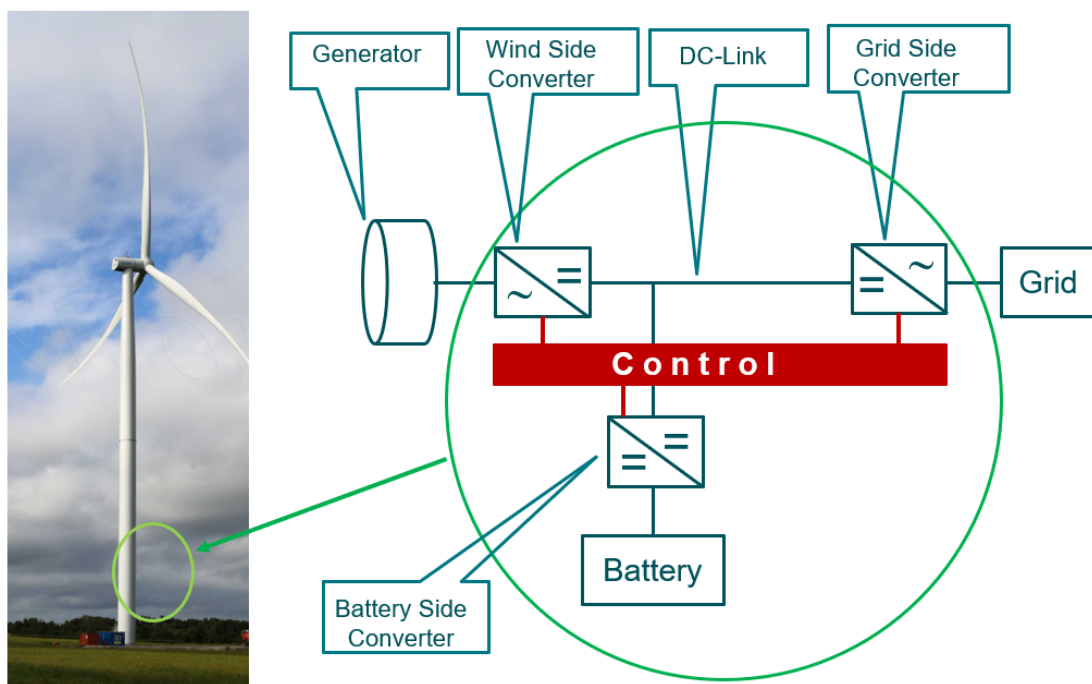


Figure 3.7: BESS integrated wind power system with multi-source converter scheme

Designing a Battery Energy Storage System (BESS) interfaced wind power system involves several key components and considerations to ensure effective integration, energy management, and grid stability. This configuration outlines a comprehensive BESS-interfaced wind power system designed to optimize energy generation, storage, and grid integration. The integration of BESS with wind energy not only mitigates the intermittency of wind power but also enhances the flexibility, reliability, and economic viability of renewable energy systems. Future developments in battery technology, control algorithms, and grid integration strategies will further refine and improve such systems. The implementation of the proposed topology concepts and

3.10 Proposed BESS Interfaced Wind Power System configuration

methodology and results are discussed in the next chapters. Limitations of this design topology are discussed in Table 3.3

Table 3.3: Limitations of DC-Link integrated BESS in wind power system

Aspect	Limitations
Coupled Operation	Tightly integrated with the wind turbine's control Cannot operate independently from the turbine
Sizing Constraints	Battery size is limited by the DC-link voltage/current ratings and thermal constraints of the back-to-back converter
Limited Grid Services	Grid services are limited due to lack of independent interface
Complex Control Coordination	Requires precise coordination with the generator-side and grid-side converters May complicate controller design
Application Limitation	Mostly useful for local power smoothing, LVRT support, and short-duration buffering not for long-duration energy storage

4 Methodology And Implementation Concepts

In this chapter, the general framework of the battery energy storage integrated wind power system conceptual design and control methodology is being explained and discussed with insights into control parameters schemes and their implementation.

4.1 Methodology Overview

The integration of wind turbine electricity into the electrical grid can introduce fluctuations in power output due to the variable nature of wind. To address this issue and improve power quality, a hybrid system incorporating Battery Energy Storage Systems (BESS) offers a viable solution. BESS can rapidly charge or discharge, making them effective for smoothing out the output power of wind turbines and providing various grid services such as peak shaving, load leveling, and frequency regulation.

In this research, a grid-connected wind power system with integrated BESS is developed and studied through simulations to evaluate its behavior under different grid conditions. The BESS is connected to the DC-link of a type-4 wind turbine using a DC-DC converter, leveraging the existing grid-side DC-AC converter for power transfer. This topology allows for the integration of one or more battery storage devices, such as batteries, to enhance the system's flexibility and efficiency.

The battery system is designed to be housed within the wind turbine tower, utilizing available space and providing shelter for the batteries. This approach minimizes costs and improves the overall efficiency of the wind turbine. The battery modules are installed on a rack inside the tower, facilitating easy maintenance and replacement when necessary.

A control system is developed to manage the operation of the BESS, including controlling the DC-link voltage and regulating power transfer to the grid based on wind speed and grid requirements. The system controller can also provide ancillary services and black start capability to ensure reliable operation, maintain power quality, and enhance grid stability.

Overall, integrating BESS into wind power systems offers significant benefits in terms of improving power quality, enhancing grid stability, and maximizing the efficiency of renewable energy generation. This research aims to further understand and optimize the performance of such integrated systems through comprehensive simulations and analysis.

4.2 Integration Of BESS at DC-link of Wind Power System

The proposed designed system in which a Battery Energy Storage System (BESS) is introduced at the DC-link of the wind turbine is shown in figure 4.1. The system comprises several sub-blocks, including the wind side converter, grid side converter, and their respective control blocks. Additionally, there are control systems designed to regulate the DC-link voltage and output power.

The wind side converter is responsible for converting the variable AC output from the wind turbine generator into DC power. This DC power is then fed into the DC-link, where the BESS is integrated. The grid side converter converts the DC power from the DC-link into AC power suitable for grid connection.

The control blocks associated with both converters ensure smooth and efficient operation of the system. They regulate the power flow between the wind turbine, BESS, and the grid, optimizing energy production and grid stability [49]. Additionally, control systems for the DC-link voltage and output power are implemented to manage the performance of the BESS and maintain desired operating conditions.

Overall, this integrated system aims to enhance the dispatchability of wind energy by utilizing BESS for power smoothing and grid support. Through comprehensive simulations and analysis, the behavior and performance of the system under various operating conditions can be evaluated, facilitating the optimization of renewable energy integration and grid stability [50] In the proposed hybrid model, the traditional roles of the grid-side converter and machine-side converter are altered to accommodate the integration of the Battery Energy Storage System (BESS) at the DC-link of the wind turbine.

Typically, the grid-side converter is responsible for regulating the DC-link voltage, ensuring stability and compatibility with the grid. Meanwhile, the machine-side converter controls the active power (P) at the wind turbine terminal, managing the power output of the turbine.

However, in this hybrid model, the BESS assumes the role of controlling the DC-link voltage. This means that the BESS control system actively monitors and

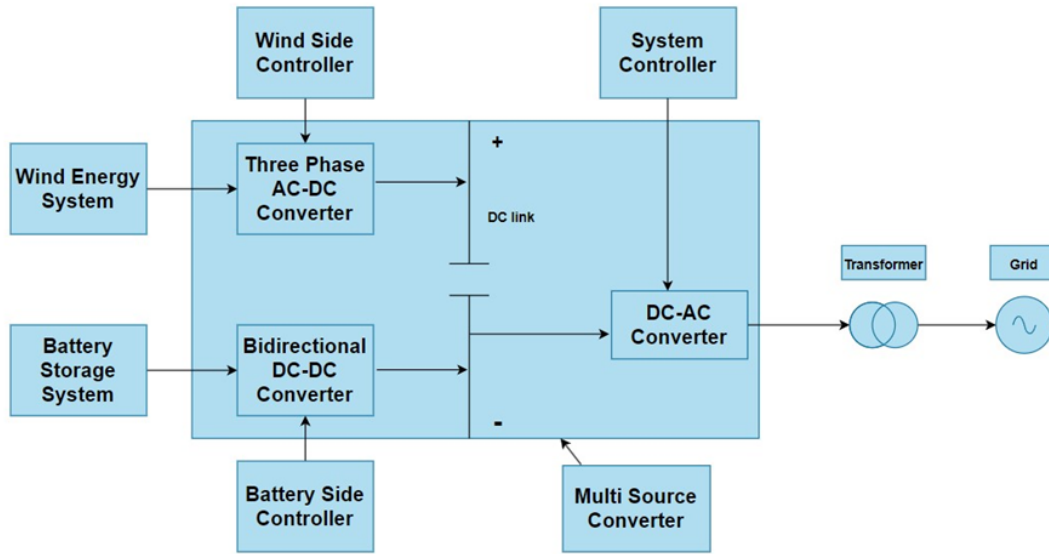


Figure 4.1: Block Diagram of BESS integrated wind power system multi-source converter scheme

adjusts the DC-link voltage to maintain optimal levels, ensuring efficient operation and grid compatibility.

By allowing the BESS to control the DC-link voltage, the system gains additional flexibility and responsiveness. The BESS can dynamically adjust its charging and discharging rates to stabilize the DC-link voltage, support grid integration, and enhance overall system performance.

This approach leverages the energy storage capabilities of the BESS to actively contribute to the stability and control of the wind turbine system, facilitating smoother integration of renewable energy into the grid and improving overall grid stability.

4.3 Type-4 wind turbine model with BESS in PSCAD

Type-4 wind turbine model in PSCAD involves several individual components, including modeling the wind turbine components, such as the generator, converter, and control system. Below is a simplified overview of a Type-4 wind turbine simulation model in PSCAD:

- **Generator Model:**

Start by modeling the synchronous generator or induction generator used in the Type-4 wind turbine. Specify the generator parameters such as rated power, voltage, and frequency.

- **Converter Model:**

Model the grid-side converter and machine-side converter using appropriate PSCAD components such as PWM Voltage Source Converters (VSC) or other converter models available in the PSCAD library. Connect the converters to the generator and the grid, ensuring proper synchronization and control.

- **DC-Link Modeling:**

Model the DC-link capacitor and any associated components such as resistors or inductors. Implement control algorithms to regulate the DC-link voltage, which may involve feedback control loops.

- **Battery Energy Storage System (BESS):**

Integrate the BESS into the model by adding battery components such as battery modules, DC-DC converters, and control systems. Connect the BESS to the DC-link and implement control algorithms to manage battery charging, discharging, and voltage regulation.

- **Control System Modeling:**

Develop control algorithms for the wind turbine system, including pitch control, speed control, and power control. Implement control logic to coordinate the operation of the generator, converters, and BESS to optimize power generation and grid interaction.

- **Simulation and Analysis:**

At the end, simulations are performed to evaluate the performance of the Type-4 wind turbine system integrating with BESS under various operating conditions. Analyze simulation results to assess system stability, power quality, and grid integration capabilities.

The available wind mechanical power is retrieved by the mechanical system and turned into mechanical torque. An electrical system then converts this mechanical torque into an electrical. The mechanical energy is converted into electrical energy by a permanent magnet (PM) machine which acts as an interface between the two systems.

4.4 Multisource Converter Scheme

A multi-source converter is a topology providing an integration of more than one energy source to a DC-link via point of common coupling(PCC). The proposed system configuration is shown in figure 4.2. DC-link is connected to the grid via a voltage source converter (VSC)

Benefits:

- Make use of existing DC-AC converter (GSC)
- Lower power electronics involved
- Less complexity
- More economical
- Less area required

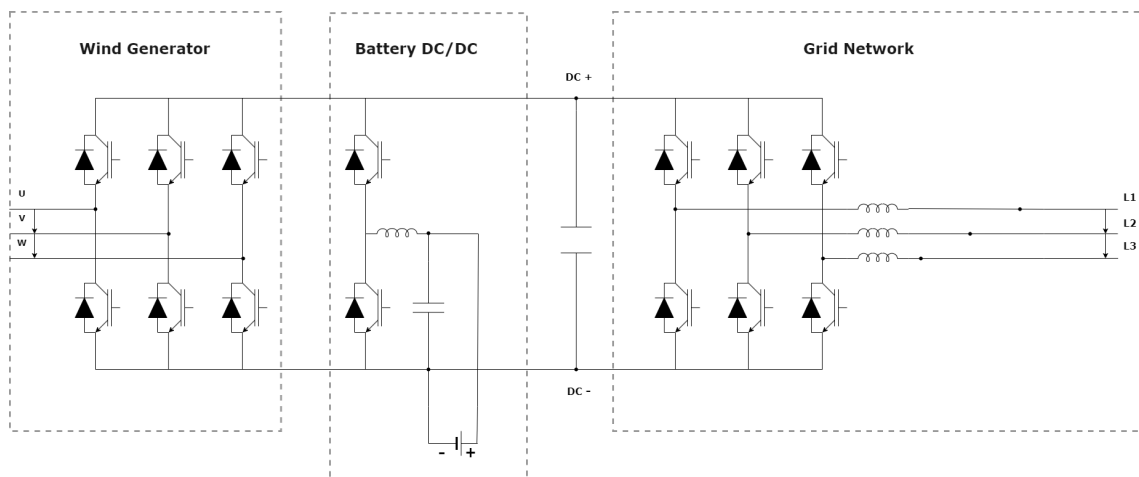


Figure 4.2: Multi Source Converter Scheme

A multi-source power converter is used to efficiently convert electrical energy from multiple input sources into a desired output voltage or current. This converter is particularly useful in applications where there are multiple sources of power available, such as renewable energy systems (solar, wind, etc.), hybrid energy systems, or storage systems [51].

4 Methodology And Implementation Concepts

The main purpose of a multi-source power converter is to manage and integrate power from different input sources, ensuring optimal utilization and reliability. It typically includes control algorithms to dynamically adjust the power flow from each source based on factors such as availability, efficiency, and load demand.

- **Key features of multi-source power converters may include:**

Multiple Input Interfaces: These converters have interfaces to connect to various input sources, such as solar panels, wind turbines, batteries, grid power, or generators.

Power Management: The converter intelligently manages the power flow from each source to the output, considering factors like energy availability, demand, and efficiency.

Bidirectional Power Flow: Many multi-source converters support bidirectional power flow, allowing energy to be transferred between input sources and the output load bidirectionally. This feature is essential for applications like energy storage systems or grid-tied systems with energy export capabilities.

Efficiency Optimization: They often employ sophisticated control algorithms to optimize the overall system efficiency by dynamically adjusting parameters like switching frequency, duty cycle, and output voltage/current.

Fault Tolerance and Reliability: These converters are designed to ensure reliable operation even in the presence of faults or failures in individual input sources. Redundancy and fault-tolerant control strategies may be employed to enhance system reliability.

Control and Management: A sophisticated control system governs the operation of the converter. It monitors input and output parameters, analyzes system conditions, and adjusts converter settings to optimize performance. This control system ensures that the converter operates efficiently and reliably under various operating conditions [52].

Grid Integration and Synchronization: In grid-connected applications, multi-source converters must synchronize with the grid and comply with relevant grid codes and standards to ensure stable and safe operation.

Overall, multi-source power converters play a crucial role in modern power systems by enabling efficient utilization of diverse energy sources and enhancing the reliability and flexibility of power generation and distribution systems [53].

The active and reactive power injected into grid is described as

$$P = \frac{3}{2} (V_d I_d + V_q I_q) \quad (4.1)$$

$$Q = \frac{3}{2} (V_q I_d - V_d I_q) \quad (4.2)$$

Grid is aligned with d axis so V_q is zero so active power P is controlled through d component of current i_d and reactive power Q is controlled through q component of current i_q .

$$P = \frac{3}{2} (V_d I_d) \quad (4.3)$$

$$Q = -\frac{3}{2} (V_d I_q) \quad (4.4)$$

4.5 An Innovative Battery Energy Storage System

An innovative battery energy storage system (BESS) would incorporate advanced technologies and design principles to address key challenges and improve performance [54]. Here's a conceptual outline of such a system:

Advanced Battery Chemistry: The BESS would utilize cutting-edge battery chemistries with high energy density, rapid charging capabilities, and long cycle life. This could include next-generation lithium-ion chemistries, solid-state batteries, or emerging technologies such as lithium-sulfur or lithium-air batteries.

Modular Design: The BESS would feature a modular design that allows for scalability and flexibility. This modular approach enables easy expansion or contraction of the storage capacity based on the specific needs of the application, whether it's a small-scale residential system or a large-scale utility-grade installation.

Smart Energy Management System: A sophisticated energy management system (EMS) would control the operation of the BESS, optimizing charging and discharging cycles based on factors such as energy demand, grid conditions, weather forecasts, and electricity prices. Machine learning algorithms could be employed to continuously optimize the performance of the system and adapt to changing conditions over time [55].

Grid Integration Capabilities: The BESS would be designed for seamless integration into the grid infrastructure, with bi-directional power flow capabilities and grid-forming capabilities if needed. This allows the system to provide ancillary services such as frequency regulation, voltage support, and peak shaving, enhancing grid stability and reliability.

4.5 An Innovative Battery Energy Storage System

Fast Response Time: The BESS would have ultra-fast response times, enabling rapid ramping of power output to support grid stability during transient events such as sudden changes in renewable energy generation or unexpected load fluctuations. This capability is critical for maintaining grid stability in systems with high penetrations of renewable energy.

Energy Arbitrage and Revenue Generation: The BESS would leverage advanced energy trading algorithms to participate in energy markets and maximize revenue opportunities. By buying electricity during off-peak hours when prices are low and selling it during peak demand periods when prices are high, the system can generate additional income while providing valuable grid services.

Safety and Sustainability: Safety features would be integrated into the design to prevent thermal runaway and mitigate the risk of fire or other hazards. Additionally, the system would prioritize the use of sustainable materials and manufacturing processes, as well as end-of-life recycling and disposal practices to minimize environmental impact.

Overall, an innovative battery energy storage system would combine advanced battery technology with intelligent control systems and grid integration capabilities to provide reliable, flexible, and sustainable energy storage solutions for a wide range of applications [56].

The integration of battery storage systems into modern renewable energy systems, particularly wind energy systems, has indeed become increasingly important for ensuring grid stability and maximizing the utilization of renewable energy resources. Here's a breakdown of the key aspects involved:

Energy Storage: Batteries play a crucial role in storing excess energy generated by renewable sources such as wind turbines during periods of low demand or high generation. This stored energy can then be discharged when demand is high or generation is low, helping to balance the grid and mitigate the intermittency of renewable energy sources.

Peak Shaving: Batteries can also serve as a source of power during peak demand periods when the load on the grid is high. By discharging stored energy during these times, batteries can help alleviate stress on the grid and reduce the need for expensive peaker plants or additional grid infrastructure.

Conceptual Design: The design of battery systems for wind turbines involves determining the optimal capacity and configuration of the batteries based on factors

4 Methodology And Implementation Concepts

such as wind turbine capacity, energy generation patterns, grid requirements, and economic considerations. This may include sizing the battery capacity to match the wind turbine's output and selecting the appropriate battery chemistry and configuration.

Integration into Simulation Models: Battery systems are integrated into wind turbine simulation models to assess their impact on system performance and evaluate different control strategies. This allows researchers and engineers to optimize the operation of the entire wind energy system, including the interaction between the wind turbine, battery storage, and grid.

Overall, the integration of battery storage systems into wind energy systems offers significant benefits in terms of grid stability, flexibility, and the efficient utilization of renewable energy resources. As battery technology continues to advance and costs decline, we can expect to see even greater adoption of battery storage in renewable energy systems worldwide [57].

Today's most common utilization is energy arbitrage, also known as energy-time shift, which implicates storing energy amid times of low requirement and re-introducing it into the grid amid times of high demand, routinely on a regular basis, to support the system's balance. Energy storage systems (ESS) technologies have existed for quite a long time and are becoming of paramount importance in the 21st century due to the smart grid [58]. Recently, slowly the concept of electric generation has been shifting from the use of non-renewable energy sources (coal, oil, etc.) to renewable sources (wind, solar, geothermal, etc.). Due to the penetration of renewable energy sources into present-day power systems, the use of energy storage system management is growing. The evolution of the concept of energy storage systems undoubtedly offers new opportunities, challenges, and numerous advantages. Over the past few decades, many new advances have been made in this field of energy storage systems. These energy storage systems offer a number of advantages like frequency regulation, transient stability, voltage support, flicker compensation, spinning reserve, uninterruptable power supply, load leveling, and peak shaving among others.

4.6 Battery Shepherd model in PSCAD

Battery Shepherd model in PSCAD provides a comprehensive simulation framework for designing, analyzing, and optimizing battery energy storage systems within the context of power system simulations. A battery shepherd model is used during this research work as shown in figure 4.4 to incorporate control and management algorithms to govern the charging and discharging of the battery based on various factors such as energy demand, grid conditions, and system requirements. These algorithms would ensure optimal operation of the battery system while maintaining safety and reliability [59].

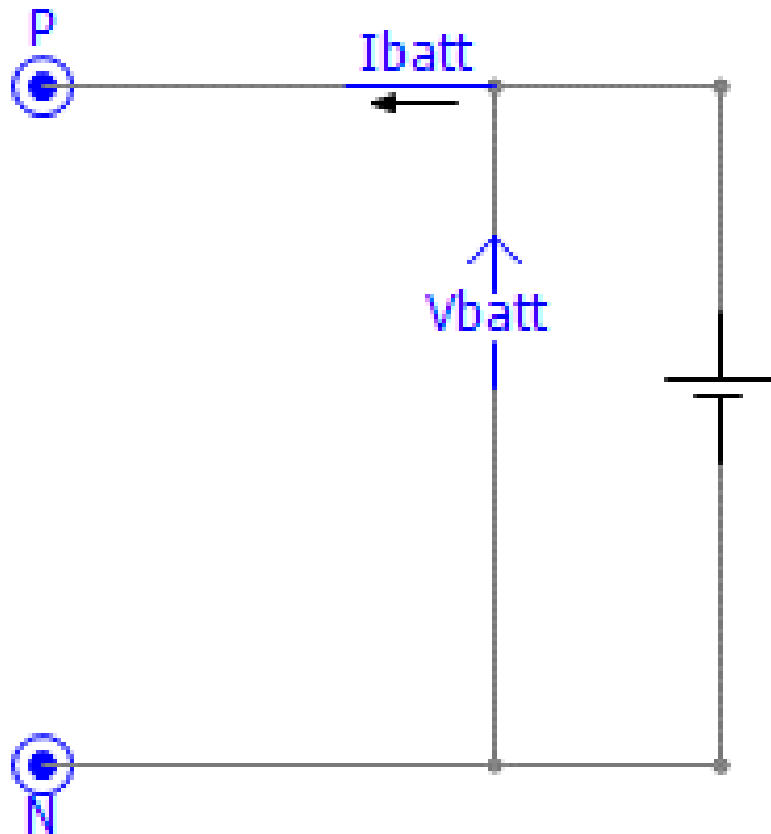


Figure 4.4: Battery Shepherd model in PSCAD

4 Methodology And Implementation Concepts

This battery model has a few limitations and is based on some simplifying assumptions mentioned below.

Assumptions:

- Internal resistance is considered to remain constant throughout the charging and discharging cycles.
- Internal resistance is unaffected by current amplitude.
- Because the discharge and charge characteristics are believed to be the same, the battery's discharge characteristics curve is utilized to calculate the battery parameters.
- The battery's capacity is unaffected by current amplitude (No Peukert effect).
- The model's behavior is unchanged by temperature.
- Battery properties are unaffected by charging and discharging histories (No hysteresis).

Limitations:

- The battery voltage cannot be negative, and there is no limit to the maximum battery voltage.
- The battery's capacity cannot be negative, and its maximum capacity is unrestricted.

The Battery Shepherd model would also include features to simulate the integration of the battery system into the grid infrastructure. This may involve modeling grid connection points, power converters, and control interfaces to regulate the flow of power between the battery system and the grid. To achieve these features a buck-boost converter is attached to this battery model which is explained in the next section.

4.7 Buck/Boost Converter and Control

4.7.1 Buck/Boost Converter

In a Battery Energy Storage System (BESS), the Buck-Boost converter as shown in figure 4.5 plays a crucial role in managing the charging and discharging of batteries, as well as regulating the output voltage to match the system requirements [60].

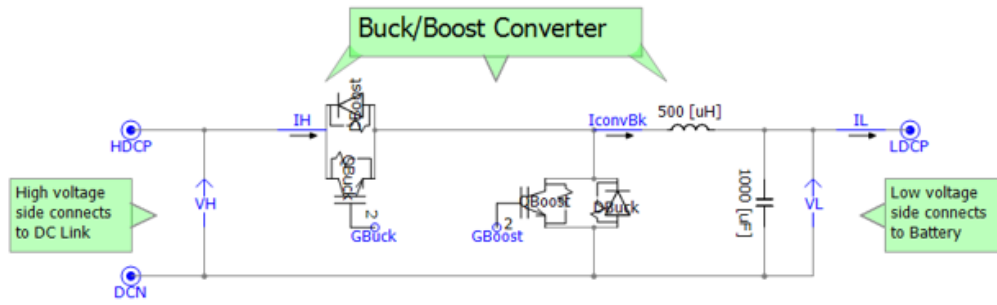


Figure 4.5: Buck-Boost Converter

4.7.2 Buck/Boost Converter Control Scheme

The operation of the buck-boost converter to charge and discharge the battery pack is done by the control system which also controls the DC-link voltage and output power to the grid as shown in figure 4.6 The mode control is used here to turn on

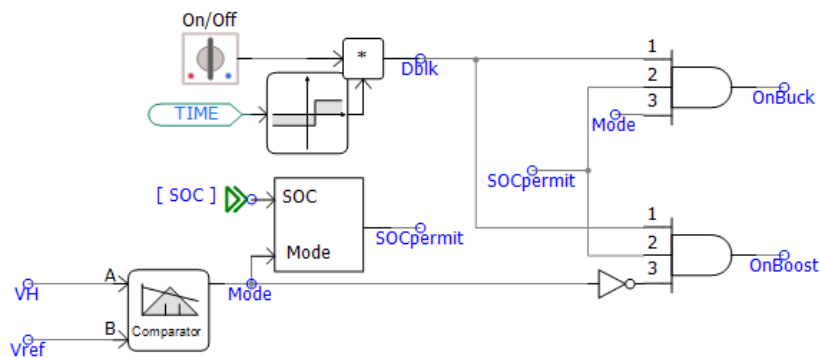


Figure 4.6: Buck-Boost Converter Control

the buck or boost control signals “OnBuck” and “OnBoost” depending upon the DC-link voltage. When the high side voltage of the buck/boost converter is greater than the setpoint DC-link voltage “Vref”, the output of the comparator is “1” which enables the “OnBuck” signal, and when the high side voltage is less than “Vref”, the output of the comparator is “0” which enables the “OnBoost” control signal to discharge the battery.

Here's how Buck-Boost converters and their control are utilized in a BESS:

Charging and Discharging Control:

Buck Mode (Charging): When the battery voltage is higher than the desired charging voltage, the Buck-Boost converter operates in buck mode to step down the voltage from the battery to the charging voltage level. This allows efficient charging of the battery from various energy sources such as solar panels or the grid.

Boost Mode (Discharging): Conversely, when the battery voltage drops below the desired output voltage, the Buck-Boost converter operates in boost mode to step up the voltage from the battery to match the load requirements, ensuring a stable output voltage.

State of Charge (SoC) Management:

The control algorithm of the Buck-Boost converter can incorporate feedback from the battery management system (BMS) to regulate the charging and discharging currents based on the battery's state of charge (SoC). This helps prevent overcharging or deep discharging of the battery, which can degrade its lifespan and performance.

Voltage Regulation:

The output voltage of the Buck-Boost converter is regulated using a control loop that adjusts the duty cycle of the switching signal based on the deviation between the actual output voltage and a reference voltage. This ensures that the output voltage remains within the desired range under varying load and battery conditions.

Efficiency Optimization:

Efficient operation of the Buck-Boost converter is essential for minimizing energy losses and maximizing the overall efficiency of the BESS. Control algorithms can be optimized to reduce switching losses, minimize conduction losses, and improve overall converter efficiency.

Grid Integration:

In grid-connected BESS applications, Buck-Boost converters may also incorporate grid-forming capabilities to synchronize with the grid and provide ancillary services such as frequency regulation and reactive power support. Control strategies for grid integration ensure seamless interaction between the BESS and the grid while maintaining stability and reliability.

Overall, Buck-Boost converters and their control play a critical role in managing the charging, discharging, and voltage regulation of batteries in a BESS, enabling efficient energy storage and delivery for a wide range of applications, including renewable energy integration, grid stabilization, and peak shaving [61] [62].

4.8 State Of Charge (SOC) Control

State of Charge (SOC) control refers to the management and regulation of the charge level within a battery or energy storage system [63]. It's a critical aspect of battery management, ensuring that the battery operates within safe limits while optimizing its performance and lifespan. SOC control involves monitoring the amount of energy stored in the battery and adjusting charging and discharging processes accordingly. Here's how SoC control typically works:

SOC Monitoring:

SOC control begins with accurate monitoring of the battery's state of charge. This can be done using various methods such as voltage measurement, coulomb counting, impedance spectroscopy, or model-based estimation algorithms. These techniques provide information about the amount of energy stored in the battery relative to its maximum capacity.

Charging Control:

During charging, SOC control regulates the charging current and voltage to ensure that the battery reaches its target SoC without overcharging. This involves adjusting the charging rate based on the battery's current SoC, temperature, and voltage characteristics. Charging may be terminated or reduced when the battery approaches full capacity to prevent overcharging.

Discharging Control:

Similarly, during discharging, SOC control regulates the discharging current to prevent the battery from being deep discharged, which can damage the battery and reduce its lifespan. Discharging may be limited or terminated when the battery reaches a minimum SOC threshold to prevent deep discharging.

SOC Estimation and Prediction:

SOC control often incorporates estimation and prediction algorithms to accurately determine the battery's SOC in real time. This may involve combining data from multiple sensors and models to account for factors such as battery aging, temperature effects, and load variations.

Safety and Protection:

SOC control includes safety features to protect the battery from operating outside its safe operating range. This may include overvoltage protection, undervoltage protection, overcurrent protection, and thermal management systems to prevent overheating [64].

The "SOC permit" is a control signal that does not permit charging or discharging when the battery SOC is greater than the maximum charging or less than the minimum discharging value. This is done by writing a script in PSCAD which is

4 Methodology And Implementation Concepts

shown in figure 4.7

```
IF (($SOC .GE. 20) .AND. ($SOC .LE. 100)) THEN
  $Comm = 1 ! Charging (Mode=0) or Discharging (Mode=1)are permitted according to "Mode"
ELSEIF ($SOC .LT. 20) THEN
  IF ($Mode .EQ. 0) THEN
    $Comm = 0 ! Block Discharging
  ELSE
    $Comm = 1 ! Permit Charging
  ENDIF
ELSEIF ($SOC .GT. 100) THEN
  IF ($Mode .EQ. 0) THEN
    $Comm = 1 ! Permit Discharging
  ELSE
    $Comm = 0 ! Block Charging
  ENDIF
ENDIF
```

Figure 4.7: SOC permit script in PSCAD

4.9 Scheduling of BESS

BESS charging and discharging is based upon the set point grid power demand P_{grid} and wind power production P_{wind} [65]. When the wind power production is less than the set point power demand towards the grid, the battery will discharge to meet the power demand and to keep the DC-link voltage stable(4.5). On the other hand, when the wind power production is higher than the set point power demand towards the grid, the battery storage system will charge the battery to keep the DC-link voltage at its nominal base value (4.6). When the wind power production is equal to the grid demand, the battery will remain idle (4.7). Incorporation of renewable energy sources and storage devices can ease the continuous operation of utility due to their self-sufficient characteristics [66].

$$P_{wind}(t) < P_{grid}(t) \quad \text{Battery Discharged,} \quad (4.5)$$

$$P_{wind}(t) > P_{grid}(t) \quad \text{Battery Charged,} \quad (4.6)$$

$$P_{wind}(t) = P_{grid}(t) \quad \text{Battery Remain Idle,} \quad (4.7)$$

The SOC limit defined is expressed in the following way

$$20\% \leq \text{SOC}(t) \leq 100\%$$

Scheduling of Battery Energy Storage (BES) involves determining the optimal charging and discharging times to maximize the economic value, grid support capabilities, and overall performance of the energy storage system. Here's how the scheduling of BES typically works:

Load and Generation Forecasting:

Before scheduling the BESS, accurate forecasts of electricity demand (load) and renewable energy generation (such as solar or wind) are essential. Load forecasting predicts the expected electricity consumption over a specific time horizon, while generation forecasting estimates the available renewable energy output.

Market Prices and Tariffs:

Consideration of electricity market prices and tariffs is crucial for scheduling the BES. By analyzing market prices, the BES can be scheduled to charge during off-peak periods when electricity prices are low and discharge during peak demand periods when prices are high. Additionally, time-of-use (TOU) tariffs may influence the scheduling strategy.

Energy Arbitrage:

BES scheduling often involves energy arbitrage, which aims to buy low-cost electricity when it's available and sell it at a higher price later. This involves charging the BES when electricity prices are low (off-peak) and discharging it when prices are high (peak).

Peak Shaving:

BES can be scheduled to provide peak shaving services, where it charges during periods of low demand and discharges during peak demand to reduce overall electricity costs and alleviate stress on the grid infrastructure.

Grid Support Services:

BES scheduling can also include providing grid support services such as frequency regulation, voltage support, and reactive power compensation. By reacting to grid signals or operator commands, the BES can help stabilize the grid and improve its reliability.

State Of Charge (SOC) Constraints:

Scheduling algorithms must consider SOC constraints to prevent the BES from overcharging or deep discharging, which can degrade battery performance and lifespan. SOC constraints ensure that the BES operates within safe limits.

Dynamic Optimization:

BES scheduling is often performed using dynamic optimization algorithms that continuously adjust the charging and discharging schedules in response to changing market conditions, load forecasts, and grid requirements. These algorithms aim to maximize the economic value and grid support capabilities of the BES in real time.

Integration with Renewable Energy Sources:

When integrated with renewable energy sources like solar or wind, BES scheduling may also involve coordinating the charging and discharging patterns to complement the intermittent nature of renewable generation and maximize the self-consumption of renewable energy.

Overall, effective scheduling of BES involves a combination of load forecasting, market analysis, optimization algorithms, and consideration of grid constraints to maximize economic benefits, grid support capabilities, and battery lifespan [67].

4.10 Impact Of Ancillary Services On Wind Turbine Simulation Model

Ancillary services play a significant role in the operation and integration of wind turbines into power systems. These are the Services necessary to support the transmission of electric power from generation to consumers given the obligations of control areas to maintain reliable operation. Required to maintain Power quality and grid stability. These services generally include

- Active power control
- Voltage ride through capability
- Reactive power compensation

Ancillary services refer to a set of services that complement the primary grid purpose of supplying energy which include system inertia, voltage control, primary frequency control, and operating reserves. The current focus is specifically on providing voltage and frequency control through storage reserves [58]. The operation of any electric grid is a balance between supply and demand. Grid frequency is often used as a good indicator of the relative balance between supply and demand. If supply exceeds demand, frequency rises. Conversely, if demand exceeds supply, grid frequency falls. With the developed simulation model this supply and demand difference can be controlled through the charging and discharging of battery energy storage system. Based on the simulation results under transient behavior on the grid side, the system parameters are checked. Parameters are grid power demand and reactive power compensation, Voltage ride through capability, wind turbine control, etc.

Here's how they impact wind turbine simulation models:

Grid Stability And Reliability:

Ancillary services provided by wind turbines, such as frequency regulation and voltage support, help maintain grid stability and reliability. In simulation models, these services are often represented through control algorithms that adjust the output

4.10 Impact Of Ancillary Services On Wind Turbine Simulation Model

of the wind turbines in response to grid frequency or voltage deviations.

Grid Code Compliance:

Many grid codes require wind turbines to provide ancillary services to support grid operation and meet specific performance criteria. Simulation models are used to assess wind turbine compliance with these grid codes by simulating their response to various grid disturbances and operating conditions.

Dynamic Response Analysis:

Wind turbine simulation models are used to analyze the dynamic response of turbines to grid events and disturbances, such as faults or sudden changes in load. Ancillary services provided by wind turbines, such as inertial response and primary frequency control, are evaluated to ensure effective grid support during transient events.

Optimization Of Control Strategies:

Simulation models are used to optimize the control strategies of wind turbines for providing ancillary services while maximizing energy capture and minimizing wear and tear on turbine components. This involves tuning control parameters to achieve the desired response under different grid conditions.

Market Participation:

Wind turbines can participate in electricity markets by providing ancillary services such as frequency regulation and spinning reserve. Simulation models are used to assess the economic viability of participating in these markets and optimize bidding strategies to maximize revenue while meeting contractual obligations.

Impact on Wind Farm Operation:

The provision of ancillary services may impact the overall operation and performance of wind farms. Simulation models are used to analyze the trade-offs between energy production and ancillary service provision, considering factors such as turbine availability, curtailment, and revenue potential.

Overall, ancillary services have a significant impact on wind turbine simulation models, influencing control strategies, grid integration, market participation, and overall wind farm performance [58]. Simulation-based analysis helps optimize the operation of wind turbines and ensure their effective contribution to grid stability and reliability.

Indeed, as wind power generation capacity continues to increase and wind turbines become more integrated into electrical power systems, several challenges arise, including power quality, voltage regulation, frequency control, and transient stability. Meeting grid connection requirements such as low voltage ride-through (LVRT) capability, frequency and voltage regulation, and power quality becomes essential for ensuring the secure and dependable operation of wind turbines within the grid.

4 Methodology And Implementation Concepts

The evolution of wind turbine technology has led to significant advancements in both mechanical and power electronics domains [68] [69]. Different types of wind turbines have emerged, including:

Type-I: Squirrel Cage Induction Generator (SCIG)

Type-II: Wound Rotor Induction Generator

Type-III: Doubly Fed Induction Generator (DFIG)

Type-IV: Permanent Magnet Synchronous Generator (PMSG)

Among these, Type-IV PMSG turbines have become increasingly popular due to their benefits such as variable speed operation, gearless design, compact size, low maintenance requirements, and the use of full-scale converters. The decoupling of the generating unit from the grid through the full-scale converter provides more stable control operation, especially in weak grid conditions.

However, integrating a large amount of wind-generated power through power electronics converters at points of connection (POC) or points of common coupling (PCC) in weak grids can lead to control interactions (CI) and dynamic response issues. The short circuit ratio (SCR) at the POC/PCC is a crucial factor in determining the strength of the grid. A low SCR indicates a weak grid, where power electronics converters must be carefully designed and controlled to ensure stable grid operation and mitigate dynamic response issues.

In summary, the integration of wind power into electrical power systems poses various technical challenges, including control interactions, dynamic response issues, and grid strength considerations. Advancements in wind turbine technology, particularly the adoption of Type-IV PMSG turbines and sophisticated control strategies, are essential for addressing these challenges and ensuring the reliable and efficient operation of wind power systems within the grid [70].

5 Results And Discussions

In this chapter, the simulations and results of the type-4 wind turbine model at different wind speeds as well as time series wind data and grid power setpoints are discussed and the results are presented. At an average wind speed of 10 m/s, the wind turbine is producing 2MW. The grid-side converter also controls the DC-link voltage at the base DC voltage.

The system parameters considered are

$$P_{\text{rated}} = 2 \text{ MW}$$

$$V_{\text{dc}} = 1.5 \text{ kV}$$

PMSG based wind turbine rated voltage = 0.69kV

Battery system

$$\text{Nominal voltage} = 1.2 \text{ kV}$$

$$\text{Rated capacity} = 1.7 \text{ kA} \cdot \text{hr}$$

The response of the BESS interfaced wind power system has been analyzed according to distinct scenario showcase study.

5.1 Active power production at variable wind speed

A 2MW type-4 wind turbine model simulated at a variable wind speed varying from 4 m/s to 16 m/s. The wind turbine is designed to give a rated output power of 2MW at a rated wind speed of 10 m/s. The results are shown in figure 5.1

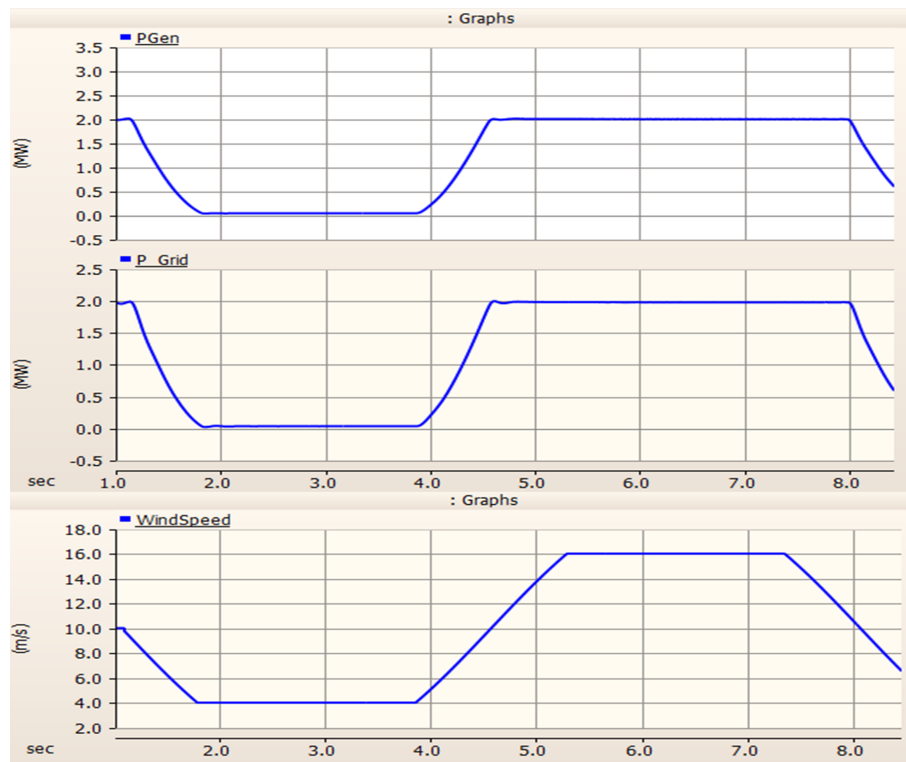


Figure 5.1: Generator and grid active power with variable wind speed

5.2 Battery energy storage system discharging at variable wind and fixed grid setpoints

The simulation model is simulated at variable wind setpoints and fixed grid power demand setpoints. There are different time intervals in which the wind speed setpoints are given as input to have a specific wind power production. The wind speed is set to specific set points to give a power output decreasing from 2MW to 1.5MW, 1MW, 0.5MW, and 0 and then increasing again to 2MW.

5.2 Battery energy storage system discharging at variable wind and fixed grid setpoints

Grid is set to have a constant power demand of 2MW. The designed control system keeps the DC-link voltage at 1.5KV and the output power demand constant at the set point value of 2MW by discharging the battery system according to the generator output as shown in figure 5.2. The combined power from the wind and battery storage system is fed to the grid through the grid-side converter.

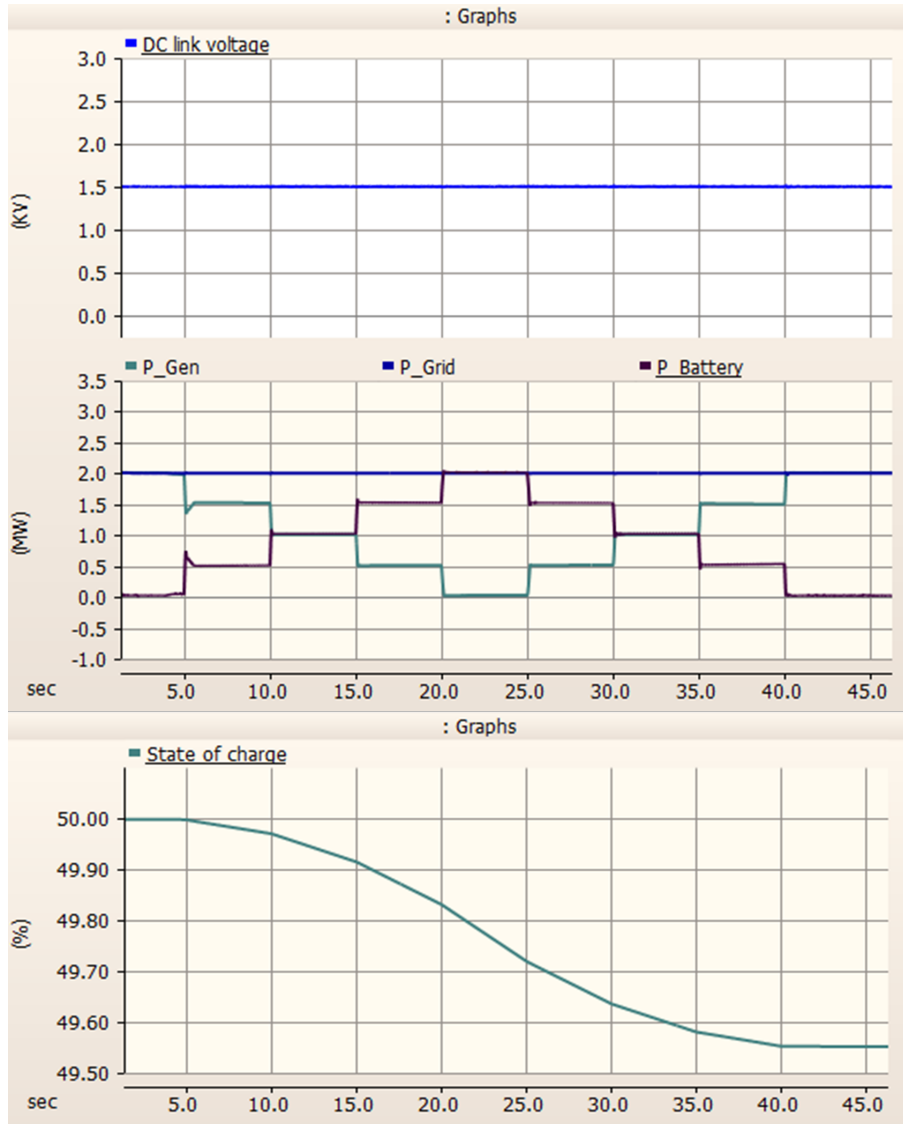


Figure 5.2: DC link voltage, power management and SOC response during BESS discharging at fixed grid setpoints

5.3 BESS discharging at variable wind and variable grid setpoints

The designed system simulated at the variable wind and also variable grid requirement to see the discharging response of the BESS. The grid active power is controlled by the d component of the grid side current as shown in figure 5.3.

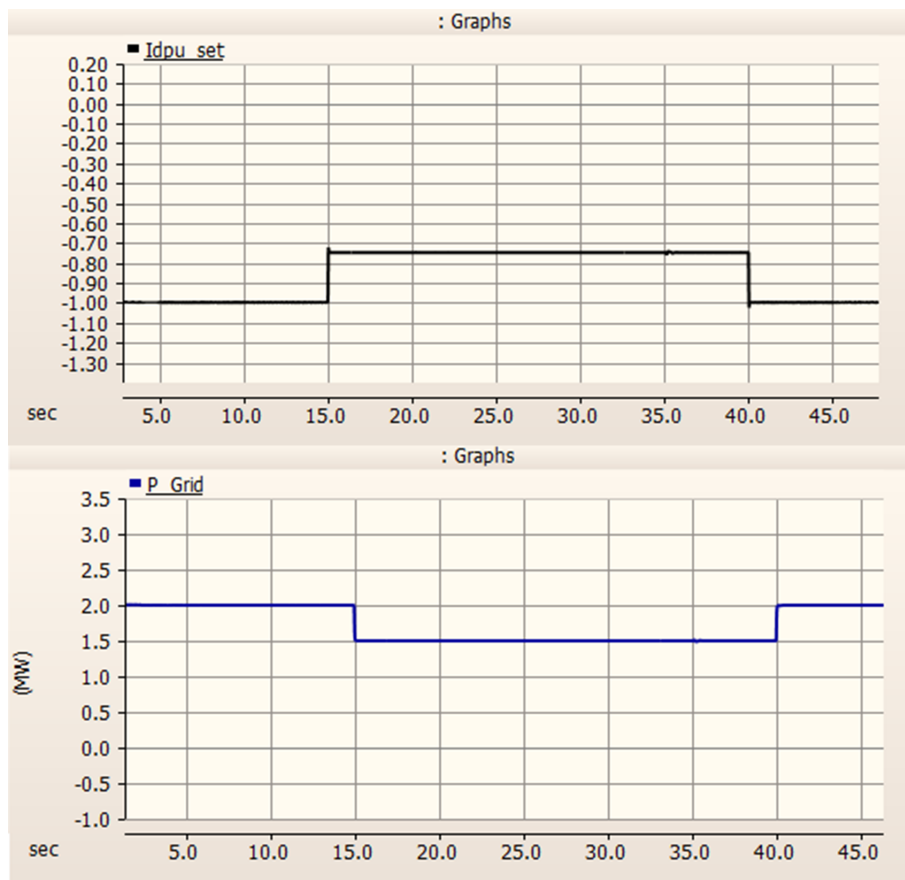


Figure 5.3: Grid set-point current and active power

The setpoint value of Id changed to reduce the grid active power demand from 2MW to 1.5MW for the time interval between 15-40 seconds, the battery will discharge according to the wind power generation and grid power setpoint as shown in figure 5.4

5.4 BESS charging at variable wind and variable grid setpoints

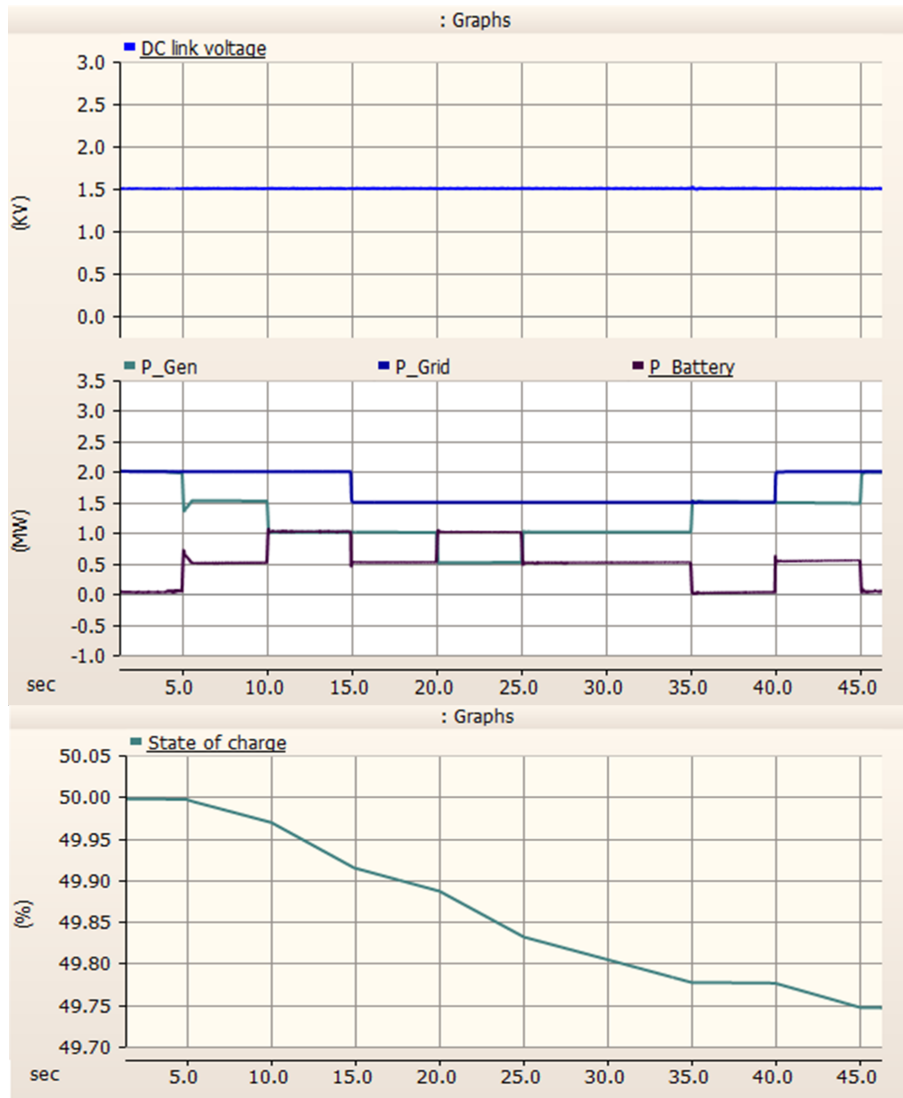


Figure 5.4: DC link voltage, power management, SOC response during BESS discharging at variable grid setpoints

5.4 BESS charging at variable wind and variable grid setpoints

The designed system also simulated at the variable wind and also variable grid setpoints to see the charging response of the battery storage system and the response of the wind turbine system. Charging at variable wind and variable grid setpoints refers to the process of charging a battery energy storage system (BESS) while

5 Results And Discussions

adapting to fluctuations in both wind energy availability and grid conditions.

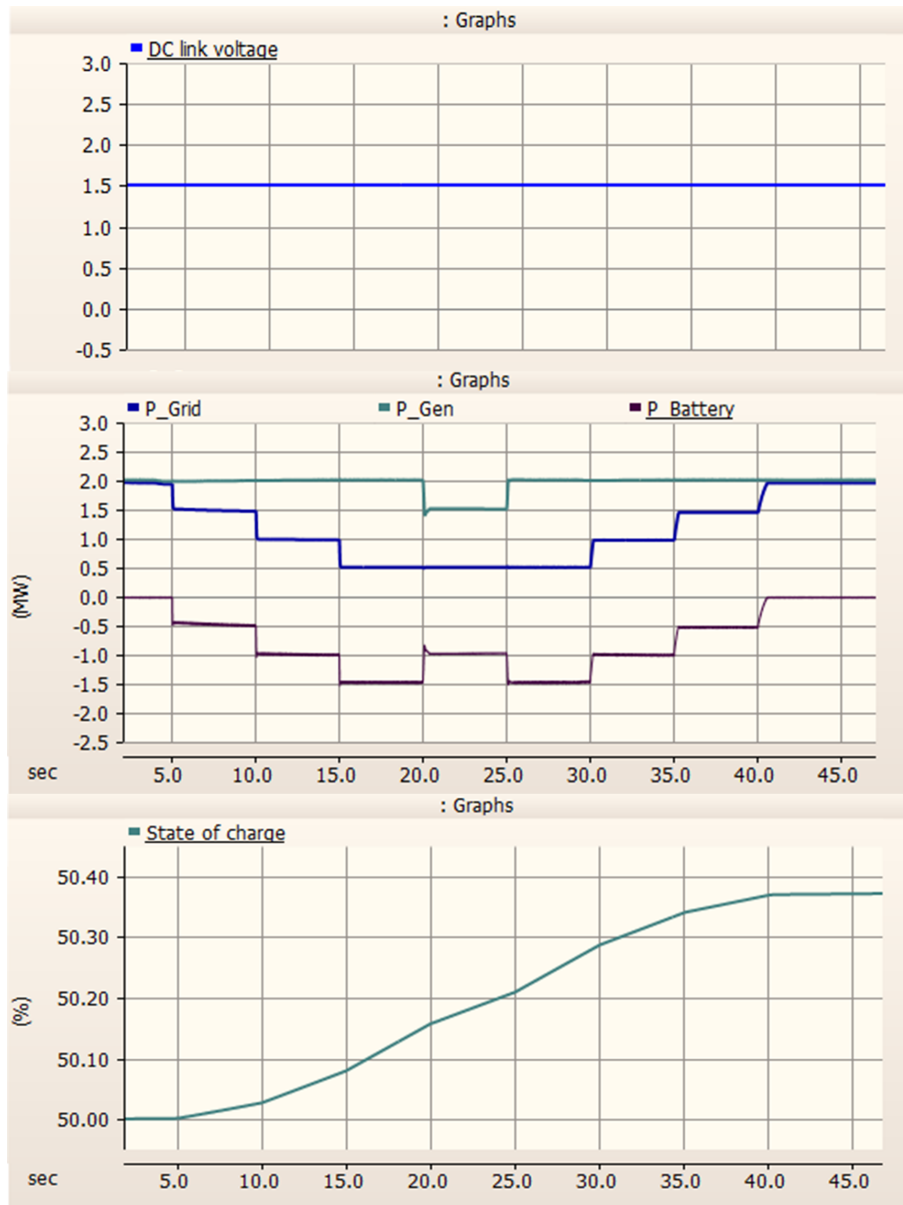


Figure 5.5: DC link voltage, power management, SOC response during BESS charging at variable grid setpoints

The designed control system charges the battery storage system depending upon the wind production and grid requirement while keeping the DC link voltage constant at 1.5KV as shown in figure 5.5

5.5 BESS charging&discharging at the variable wind and fixed grid setpoints

The designed system also simulated at variable wind and having fixed grid setpoints to see the combined charging and discharging response of the battery storage system. The results are shown in figure 5.6. The SOC of the battery storage also shows the charging and discharging response of BESS.

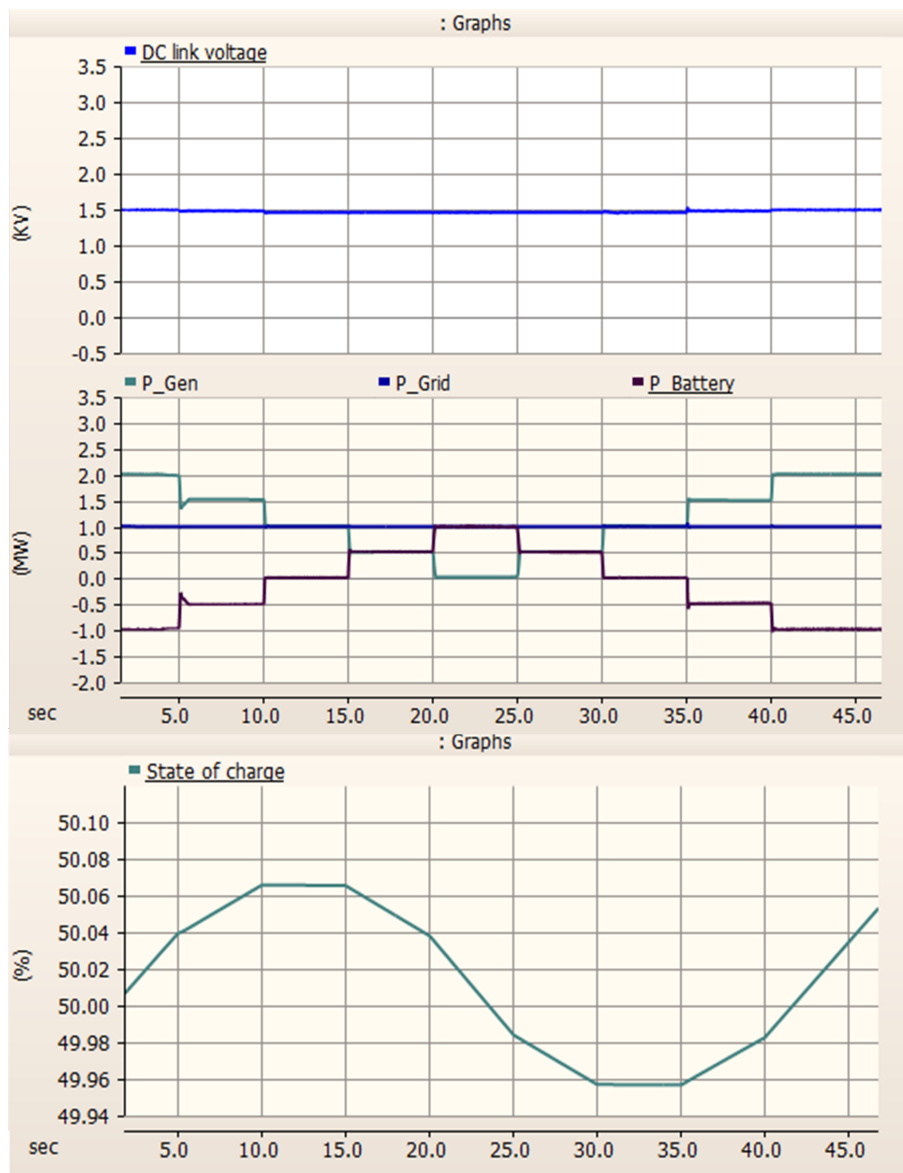


Figure 5.6: DC link voltage, power management, SOC response during BESS charging&discharging at variable wind production

5.6 BESS discharging with time series wind data at fixed grid setpoints

The designed system is now simulated with time series wind data with an average wind speed of 10m/s for a time period of 10 minutes with a fixed grid requirement of 2MW and the response of BESS observed. The results are shown in figure 5.7 When

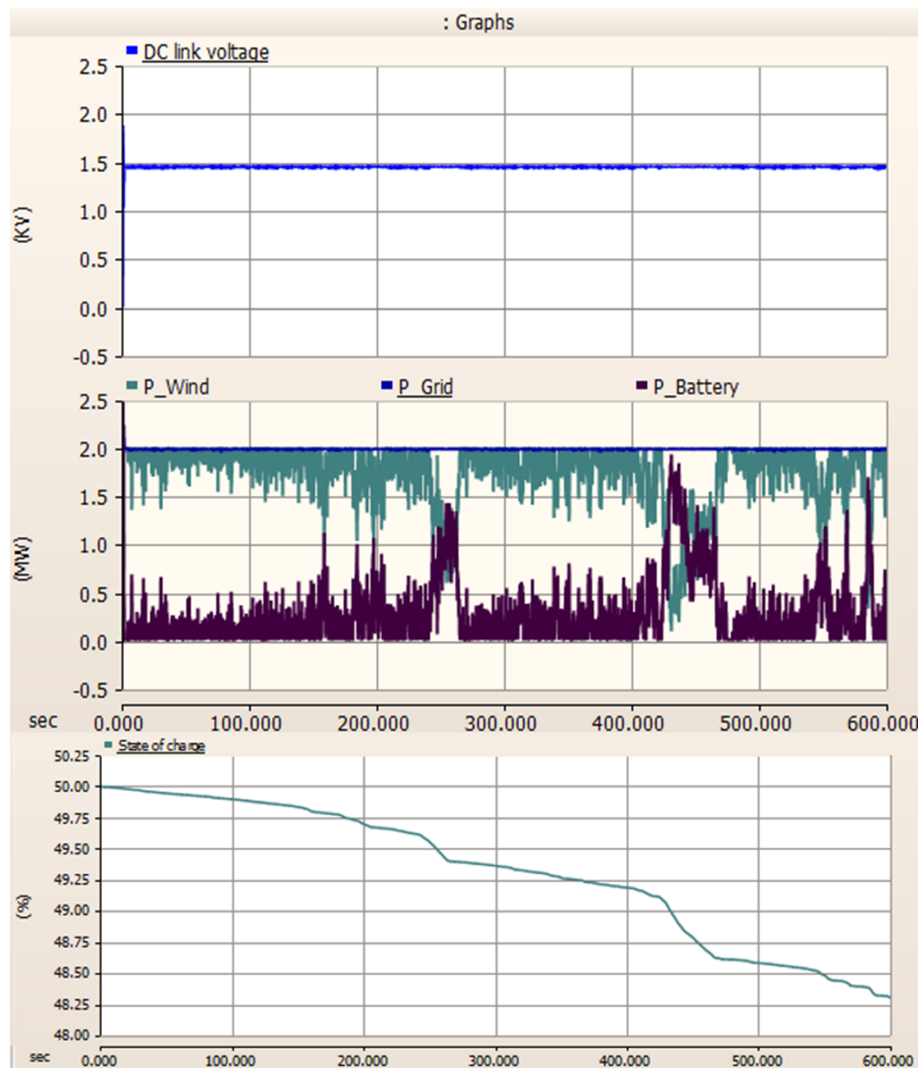


Figure 5.7: DC link voltage, power management, SOC response during BESS discharging for time series wind data

the power from the wind generator reduces due to wind fluctuations, the designed control system discharges the BESS depending upon the wind generation and grid power requirement, while keeping the DC-link at a stable value. A zoomed-in view

5.7 BESS charging&discharging with time series wind data at fixed grid setpoints

of the generated power from the wind, battery energy storage power, and grid power is shown in figure 5.8 for a period of 220s to 290s.

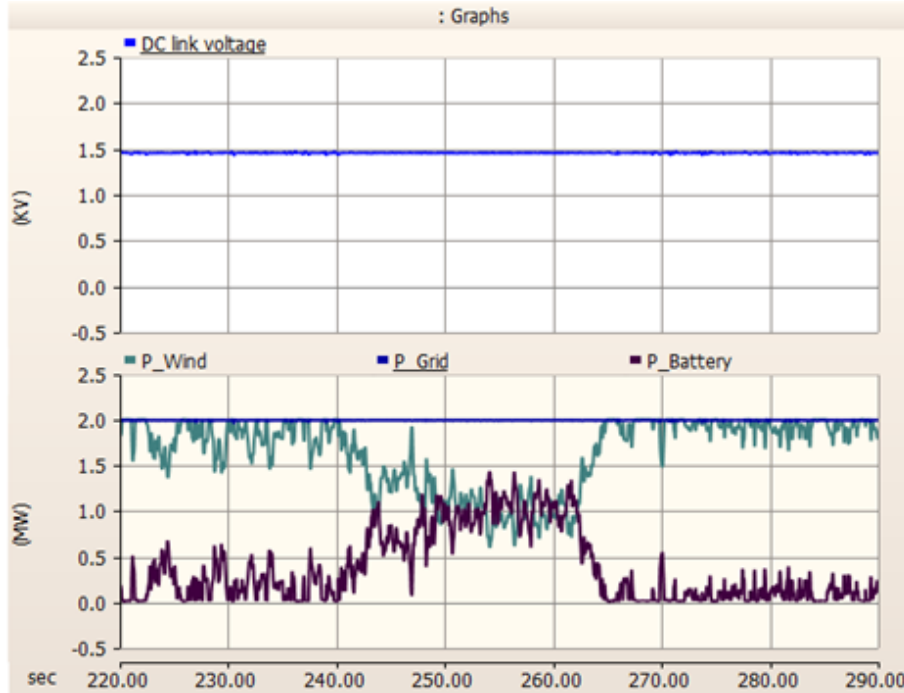


Figure 5.8: Focused view wind-generated and BESS active power response

5.7 BESS charging&discharging with time series wind data at fixed grid setpoints

To analyze the combined response of BESS now the grid power demand is at 1.3MW and time series wind data is given to the wind turbine as in the previous case. When the wind-generated power is greater than 1.3MW which is the set point required power from the grid, BESS should be charged. On the other hand, when the wind-generated power is less than the grid set point required power, BESS should be discharged. The designed control system meets the above-mentioned requirements while keeping the DC-link voltage stable at the set base value of 1.5KV shown in figure 5.9

5 Results And Discussions

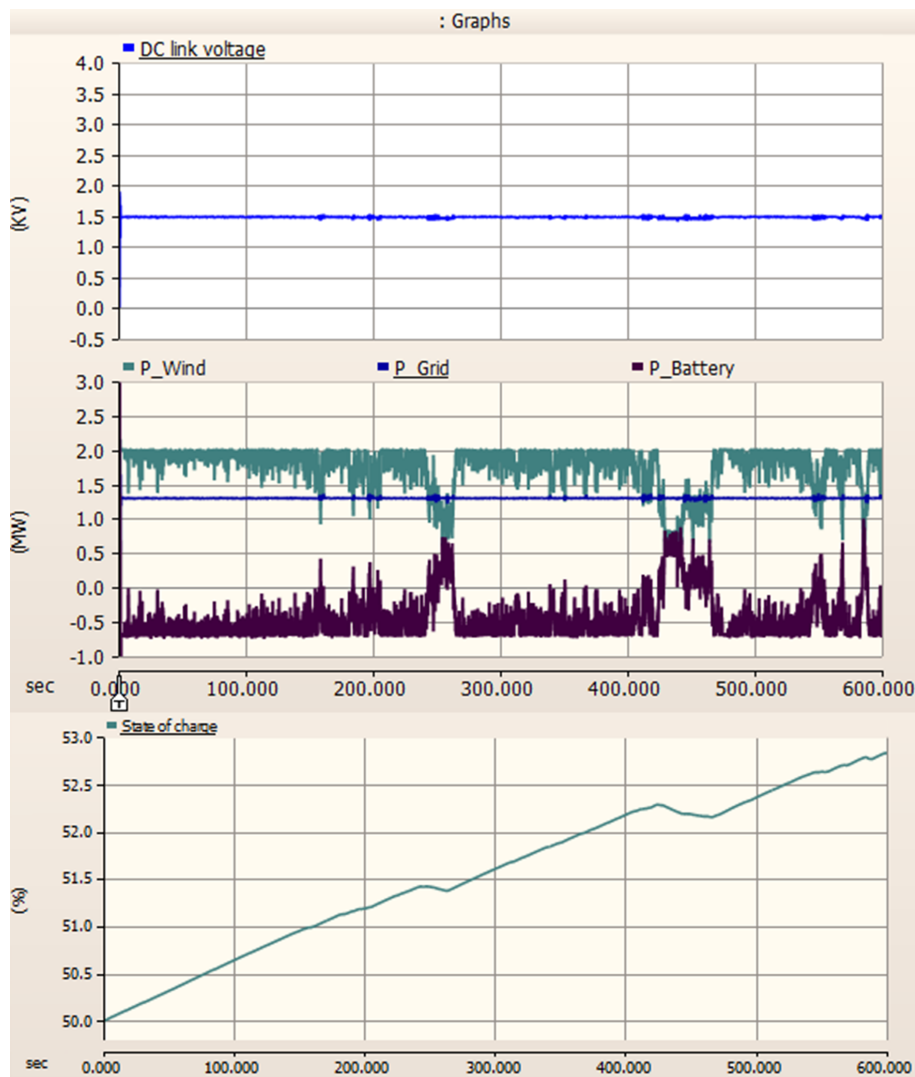


Figure 5.9: Power management through BESS charging&discharging for time series wind

Time series wind data provides information about wind power generation over time, allowing for the prediction and analysis of wind energy availability, BESS Charging involves storing electrical energy in the batteries when excess energy is available, such as during periods of low demand or high renewable energy generation, discharging occurs when stored energy is released from the batteries to meet demand or support grid stability. BESS charging and discharging with time series wind data involves using a battery energy storage system to manage the storage and release of electrical energy based on variations in wind power generation, as captured by time series wind data while adhering to predetermined grid setpoints to ensure grid stability and reliability.

5.8 Battery energy storage state of charge(SOC) permit control

To prevent the battery storage system from overcharging and deep discharging, a specific controller should be implemented. The control system operates on the basis of the SOC of the battery storage system and the current mode of operation i.e. charging or discharging. In discharging mode, when the SOC of the battery reaches a setpoint value, which is set at 20% for this model, the control system turns off the discharging and shifts the control of the DC-link from BESS to the grid side converter of the wind turbine

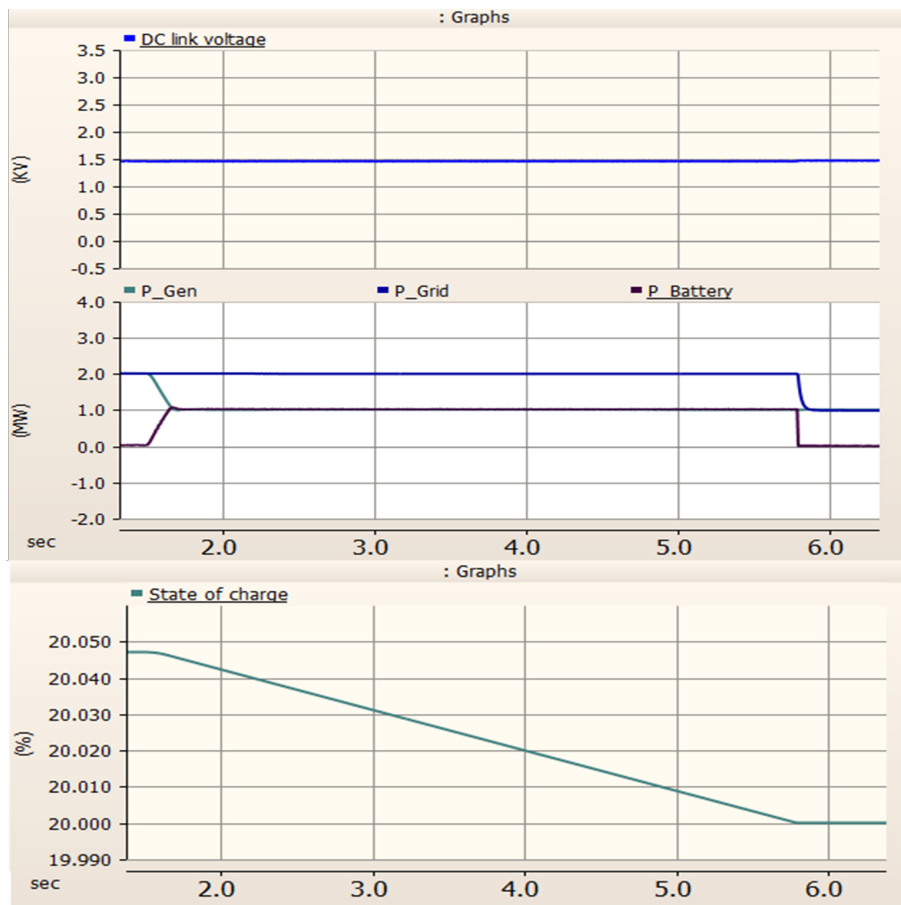


Figure 5.10: BESS SOC permit control in discharging mode

As shown in figure 5.10, the battery continues to discharge until its SOC reaches 20%. At this point, the control system turns off the battery, and the DC-link control is shifted to the grid-side converter.

5 Results And Discussions

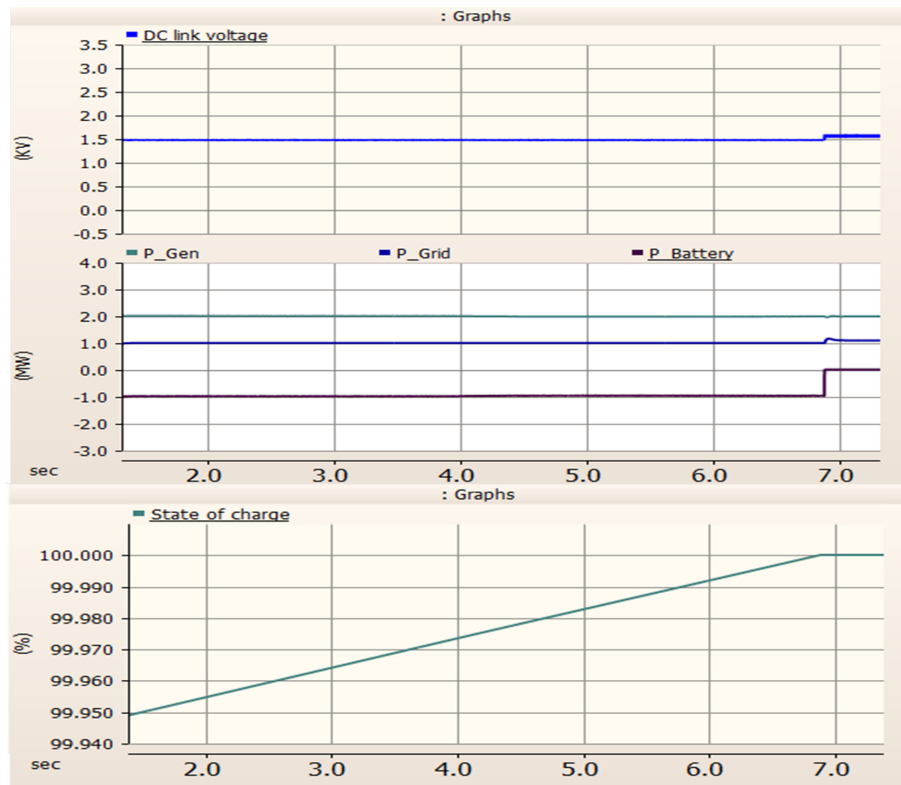


Figure 5.11: BESS SOC permit control in charging mode

On the other hand, when the battery is in charging mode and the SOC reaches to a setpoint value which is 100%, the control system again turns off the battery, and the control is shifted again to the grid side converter of the wind turbine as shown in figure 5.11

6 Enhancement in dynamics and LVRT behavior through battery energy storage system integration to the wind power system

6.1 Battery energy storage system for ride-through capability in case of dynamics

Overview

Grid integration of large wind farms indeed poses significant challenges during dynamic environments. The Short Circuit Ratio (SCR) plays a crucial role in determining the strength of the electrical grid. In weak grids, even minor disturbances at the Point of Connection (POC) can lead to unwanted control interactions and dynamic response issues. Fault events and voltage sags are particularly concerning in weak grids, as they can have a profound impact on the functioning of wind turbines.

The research focuses on enhancing the grid integration of large wind farms by integrating a Battery Energy Storage System (BESS) into wind turbine architecture [24]. The integration can be done at the Point of Connection (POC) and between a full-scale converter block at the (DC-link) connection of the wind turbine. The main objectives are to optimize and strengthen the Low Voltage Ride Through (LVRT) capability of wind turbines with the addition of a battery system and to stabilize overall system operations during fault events in different grid conditions. Optimization and strengthening of LVRT capability through BESS integration [71]. Stabilization of system operations in terms of power quality, grid voltages, and DC link voltages during fault events. Comparison of results with battery system to evaluate the impact of BESS integration on grid performance. Analysis of experimental results for each fault scenario in strong and weak grid conditions. Discussion of the effectiveness of BESS integration in improving LVRT capability and stabilizing system operations.

Overall, the study aims to contribute to the development of effective solutions

6 Enhancement in dynamics and LVRT behavior through battery energy storage system integration to the wind power system

for enhancing grid integration and system stability by integrating BESS into wind turbine architecture. The findings provide valuable insights into the performance of BESS integration.

A Battery Energy Storage System(BESS) offers a versatile and reliable solution in case of dynamics, helping to enhance grid resilience, minimize downtime, and ensure the uninterrupted supply of electricity to consumers [72]. Effective integration of BESS into grid infrastructure, coupled with appropriate control and coordination strategies, is essential for maximizing its benefits in case of dynamics.when BESS is connectet near grid at POC following benefits can be achieved

- **Voltage Support:** In a weak grid, voltage fluctuations are common, especially during faults. BESS can quickly inject or absorb reactive power to stabilize voltage levels, ensuring that sensitive equipment stays operational.
- **Frequency Regulation:** Grid frequency tends to deviate during faults or sudden changes in load. BESS can rapidly inject or absorb active power to help balance the system, providing frequency regulation services and preventing system-wide instability.
- **Black Start Capability:** In the event of a complete grid blackout, BESS can provide a reliable and fast-starting power source to initiate the restoration process. This is crucial for minimizing downtime and restoring power to critical loads as quickly as possible.
- **Fault Ride Through (FRT):** During grid faults, conventional generators may trip offline, exacerbating the problem. BESS, with its fast response time, can ride through faults by providing power support, thus helping to stabilize the grid and prevent cascading failures.
- **Load Balancing:** BESS can also help alleviate stress on the grid during peak demand periods by storing excess energy when demand is low and discharging it during peak hours. This reduces the likelihood of grid overload and enhances overall system stability.
- **Islanding Operations:** In areas prone to frequent outages or with weak grid connections, BESS can support islanded operations by providing a stable and reliable power source until the grid connection is restored.

But DC link overshoot problem still there during dynamics so installing a BESS at DC link can solve this overshoot problem by absorbing excess power coming from generation side during dynamics

6.2 Fault scenario challenges and solution through BESS

Indeed, the imbalance between generation and transmitted active power during a fault event can lead to various grid instabilities, including voltage sags or swells at Points of Connection (POC). These voltage fluctuations can have cascading effects, such as elevating DC link voltages, increasing grid currents, and accelerating generator frequency, which can further exacerbate grid instability.

In the past, wind turbines were often allowed to disconnect from the grid immediately upon detecting a fault. However, modern grid codes now mandate that wind turbines remain connected to the grid for a certain duration after a fault event before initiating disconnection. This requirement aims to enhance grid stability and resilience by ensuring that wind turbines contribute to fault ride-through capability and support grid recovery efforts [73].

By staying connected to the grid during fault events, wind turbines can help mitigate the impacts of faults and contribute to maintaining grid stability [74]. Wind energy conversion systems might experience control converter unit failure if the system is unable to enforce the FRT in the course of fault events. To mitigate these issues, it is essential that wind power units must persist to remain affixed to the electrical grid during substantial voltage drops and contribute towards the recovery and clearance process caused by symmetrical and asymmetrical faults. This recovery process is defined as fault ride through FRT, low-voltage fault ride through (LVRT). Extensive studies have shown that this LVRT process for weaker grids can be enhanced using external devices like synchronous condensers, battery energy storage systems (BESS), and FACTS devices [75].

6.3 Integartion of battery energy storage system for wind power system

Investigating the enhancement of Low Voltage Ride Through (LVRT) capability and improving the performance of a Type-IV Permanent Magnet Synchronous Generator (PMSG) wind turbine by integrating external Battery Energy Storage Systems (BESS) at the Point of Connection (POC) and in parallel with the grid-side converter (GSC) on the DC link is a promising approach. Here's how such integration could be achieved and its potential benefits

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- **Integration at Point of Connection (POC):**

Placing BESS at the POC allows for direct support of the wind turbine's connection to the grid. During voltage dips or faults, BESS can inject reactive power to support grid voltage, helping the wind turbine ride through the event without disconnecting. Fast response times of BESS can mitigate voltage fluctuations, improving grid stability and reducing the risk of turbine disconnection.

- **Integration on DC Link Parallel to GSC:**

Installing BESS in parallel with the GSC on the DC link provides additional flexibility and control over the wind turbine's operation. BESS can assist in smoothing out fluctuations in DC link voltage, enhancing the overall stability and performance of the wind turbine system. By actively managing DC link voltage, BESS can optimize power conversion efficiency and reduce stress on grid-side components.

- **Testing with a 2 MW PMSG Wind Turbine System:**

Utilizing a 2 MW PMSG wind turbine system for testing allows for a realistic assessment of the proposed strategy under typical operating conditions. Performance metrics such as LVRT capability, grid stability, and power quality can be evaluated to quantify the effectiveness of BESS integration. Field testing and simulation studies can be conducted to validate the proposed enhancements and identify any potential challenges or limitations.

Benefits:

- **Enhanced LVRT capability:** BESS integration improves the wind turbine's ability to remain connected to the grid during voltage dips or faults, reducing downtime and improving overall reliability.
- **Improved grid stability:** BESS provides fast-acting support to mitigate voltage fluctuations and grid instabilities, contributing to a more stable and resilient power system.
- **Optimal performance:** By actively managing reactive power and DC link voltage, BESS integration helps optimize the performance and efficiency of the wind turbine system, maximizing energy output and minimizing operating costs.

In general, integrating external BESS at the POC and on the DC link parallel to the GSC in a Type-IV PMSG wind turbine system offers significant potential for enhancing LVRT capability and improving overall performance. Through careful design, testing, and validation, this strategy can contribute to the advancement of renewable energy integration and grid stability in modern power systems.

6.4 Strong and weak grid concept

The terms "strong grid" and "weak grid" refer to the characteristics and capabilities of an electrical power system, particularly in relation to its ability to withstand and respond to changes in demand, generation, and disturbances. Grid strength refers to the ability of the power system to transmit generated power efficiently while maintaining stable voltage and frequency levels within acceptable limits. In a robust grid, the addition of extra loads does not result in unwanted voltage and frequency oscillations, indicating the system's capacity to handle fluctuations and maintain stability.

The importance of grid strength is particularly pronounced in wind turbine generation and distribution systems. Unlike conventional synchronous generators, which directly contribute to system stability through their inherent characteristics, wind turbines typically use inverters for grid integration at Points of Connection (POC). Inverter-based integration introduces additional complexities and challenges related to grid stability and dynamics. Short Circuit Ratio(SCR) at POC is an essential factor that classifies a strong and weak grid.

- **Strong Grid:**

A strong grid typically refers to a power system with robust infrastructure and ample generation capacity relative to demand. Characteristics of a strong grid include:

- **High Short Circuit Ratio (SCR):** The ratio of available short circuit current to the rated current of the system is relatively high, indicating a high capacity to deliver and absorb power during faults.
- **Low Impedance:** The impedance of transmission lines and other grid components is relatively low, allowing for efficient power transfer with minimal voltage drop.
- **High Stability:** The grid exhibits stable and predictable behavior, with minimal voltage and frequency fluctuations even under changing load and generation conditions.
- **High Fault Tolerance:** The grid can withstand and quickly recover from disturbances such as faults or sudden changes in generation or load.

Generally, electrical grids with SCR=10 or above are considered strong grids.

- **Weak Grid:**

A weak grid, on the other hand, refers to a power system with limited infrastructure and/or generation capacity relative to demand. Characteristics of a weak grid include:

- **Low Short Circuit Ratio (SCR):** The SCR is relatively low, indicating limited capacity to deliver and absorb power during faults.
- **High Impedance:** Transmission lines and other grid components have high impedance, leading to significant voltage drop and power losses over distance.
- **Instability:** The grid may exhibit unstable behavior, with voltage and frequency fluctuations, especially under changing load and generation conditions.
- **Limited Fault Tolerance:** The grid is more susceptible to disturbances, and faults or other disruptions can result in prolonged outages or system failures.

Generally, electrical grids with $SCR < 10$ are considered weak, and electrical grids with $SCR < 3$ are considered very weak grids [76].

The distinction between a strong grid and a weak grid lies in the resilience, stability, and capacity of the power system to maintain reliable operation under various operating conditions and disturbances. Strong grids are characterized by robust infrastructure and stability, while weak grids face challenges related to limited capacity, higher impedance, and lower fault tolerance.

The formula to calculate the SCR value is given in equation 6.1 as [77]

$$SCR = \frac{V_G^2}{Z_{weak} \cdot P_{WT}} \quad (6.1)$$

In this formula:

SCR

SCR represents the Short Circuit Ratio

V_G

stands for the grid voltage

Z_{weak}

denotes the impedance of the weak grid

P_{WT}

represents the power output of the wind turbine.

It is evident that with decreasing SCR value, the voltage oscillations and harmonics are at large. The stable power-generating wind turbine operation becomes problematic in weaker grids. In weak grids during a fault event, the wind turbine grid side

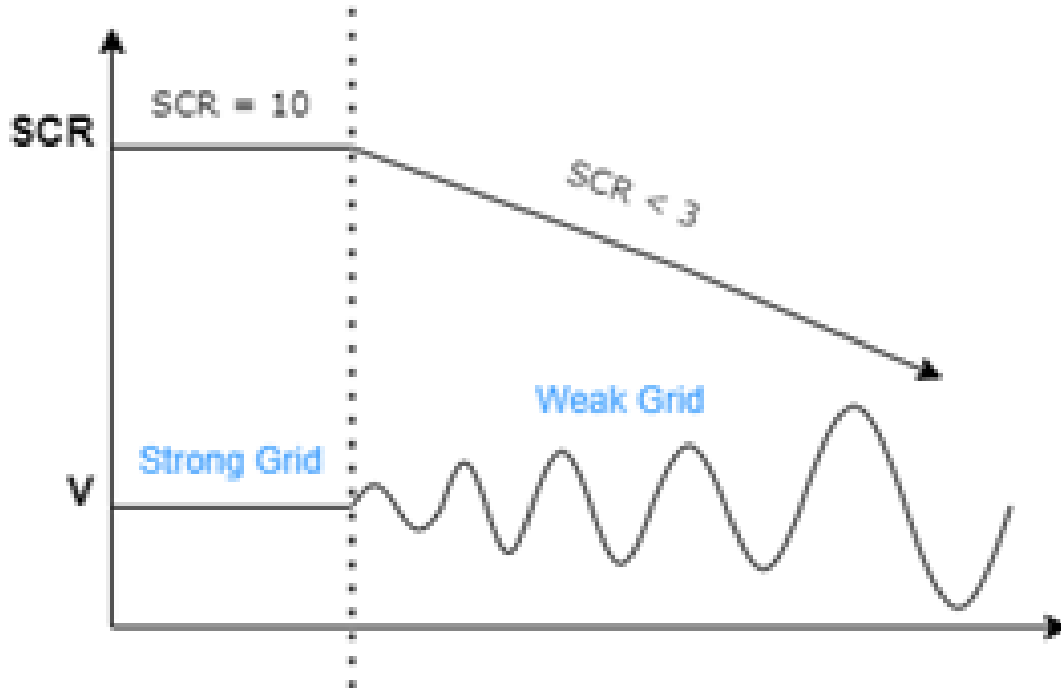


Figure 6.1: Harmonics in voltage waveform generated with decreasing SCR

control (GSC) unit becomes inefficient and ceases to provide required reactive and voltage recovery support. In these conditions, battery storage devices or other LVRT methods are recommended to provide support for the wind turbine fault recovery mode and for smooth functioning post-fault mode. The imbalance caused between the generation side active power and the transmitted active power at the grid side during the fault event causes a voltage sag or swell at POC, which further causes elevation of DC link voltages, high grid currents, and acceleration of the generator frequency and other instabilities. Additionally, it may cause the electric grid to trip and may trigger the closure of wind power plants, resulting in blackouts for extended periods. Earlier wind turbines were allowed to cut off from the grid in the event of a fault, but modern grid codes mandate the WT to stay linked to the grid amid the event of a fault for a certain time period before disconnecting the wind turbine from the grid. [73] To mitigate these issues, it is essential that wind power units persist to remain affixed to the electrical grid during substantial voltage drops and contribute towards the recovery and clearance process caused by symmetrical and asymmetrical faults. This recovery process is defined as a low-voltage fault ride-through (LVRT). During grid faults, wind farms must stay linked to the grid

and inject a specific amount of reactive current. To meet these requirements and to enhance the LVRT capability of Wind turbine power systems utilizing PMSG, a cooperative control approach is employed. This approach involves integrating a BESS and a grid-side converter (GSC). During LVRT operation, the proposed method utilizes the BESS to absorb any power imbalances within the back-to-back converters, effectively regulating the DC-link voltage [78]

6.5 Low-Voltage Ride-Through capability (LVRT) and grid codes

Low Voltage Ride Through (LVRT) is a critical requirement specified in grid codes for grid-connected renewable energy sources, including wind turbines. Grid codes define the technical requirements and standards that renewable energy systems must adhere to in order to ensure the stable and reliable operation of the electrical grid [79]. LVRT capability refers to the ability of a renewable energy system, such as a wind turbine, to remain connected to the grid and continue operating during and after a voltage dip or fault event, thereby supporting grid stability and reliability. With modern grid codes, it's anticipated that wind turbines will remain connected pre and post-fault. The modern grid codes define the expected conduct of LVRT conditions during severe load shifts or momentarily voltage dips [80]. All grid code provisions must be met by modern wind farms. Wind turbines are anticipated to function identically to classical generators, staying linked and supplying real and reactive power both before and after the voltage decrease. The German LVRT grid code requirements are presented in the figure 6.2.

As per the figure 6.2, multiple regions are displayed, namely regions A, B, and C. If a disturbance occurs in region A, the WT is required by the current electric grid regulations to uphold network connectivity amid grid failures that last up to 150 ms. If a fault occurs in region B, the wind turbine may or may not remain connected to the grid, and if any transient takes place in region C, the wind turbine may disconnect from the grid. In Germany, for example, the grid code requires that a wind power system remain connected to the grid for at least 1500 milliseconds when the system voltage dips by 0.9 P.U. The WT is anticipated to provide system support during this time period by injecting reactive power to resolve the fault condition. Similarly, if the system voltage rises beyond the upper threshold level, the wind farm shall remain connected for a set period of time.

The evolution of grid codes to address the impacts of increased wind energy penetration on power network reliability and quality is crucial for ensuring the

6.5 Low-Voltage Ride-Through capability (LVRT) and grid codes

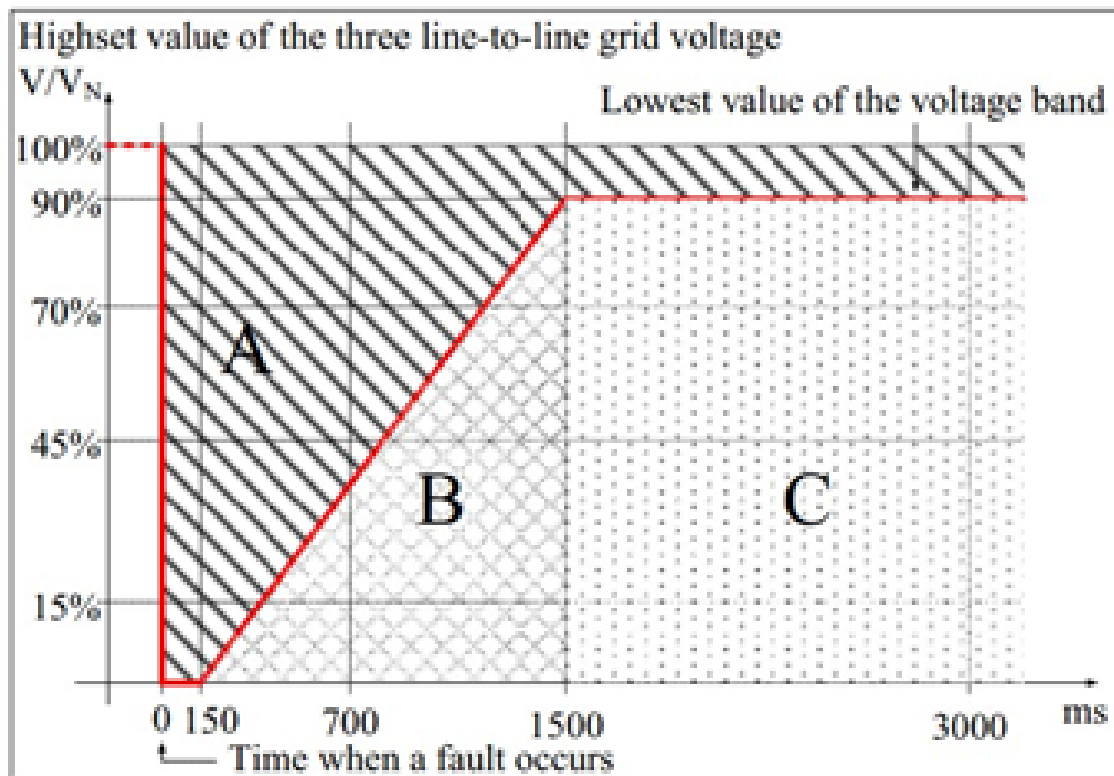


Figure 6.2: LVRT requirement in German grid code

stability of electrical grids.

Different countries have developed unique Grid codes for wind farm performance in terms of voltage drop and surges [81]. Many of the principles expressed in the Grid codes have also been adopted into standards, like IEEE 1547. The LVRT regulations for numerous countries are depicted in figure 6.3

6 Enhancement in dynamics and LVRT behavior through battery energy storage system integration to the wind power system

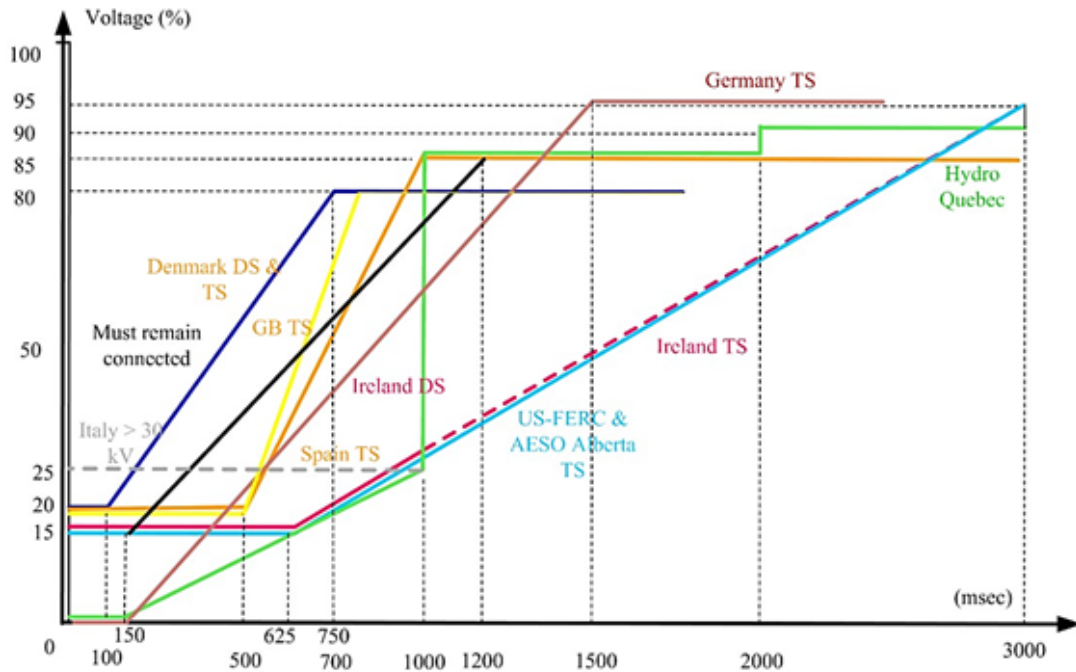


Figure 6.3: Grid code requirements of different countries

6.6 Battery energy storage system integration for ride-through capability in case of dynamics

The application of Battery Energy Storage Systems (BESS) for ride-through capability during dynamics, such as faults or disturbances in electrical grids, is becoming increasingly popular nowadays. This can provide a fast and precise response to grid dynamics, helping to stabilize voltage and frequency levels during faults or disturbances.

During grid faults, wind farms must stay linked to the grid and inject a specific amount of reactive current. To meet these requirements and to enhance the LVRT capability of wind turbines utilizing PMSGs, a cooperative control approach is employed. This approach involves integrating a BESS and a grid-side converter (GSC). During LVRT operation, the proposed method utilizes the BESS to absorb any power imbalances within the back-to-back converters, effectively regulating the DC-link voltage [78].

6.6.1 Battery energy storage system integration at DC-link for dynamics

For this approach, a battery energy storage system is added at the DC-link for mitigation of voltage deviations during different dynamics. Battery compensation at the DC-link for dynamic studies involves the utilization of Battery Energy Storage Systems (BESS) to support wind turbines or other renewable energy systems during grid disturbances. By ensuring continuous operation during fault events, wind turbines equipped with BESS at the DC-link can contribute to grid stability and reliability, supporting the increased penetration of renewable energy into the electrical grid. Battery compensation at the DC-link for LVRT enhances the performance and reliability of wind turbines by providing rapid and precise voltage support during grid disturbances. By ensuring continuous operation and grid connection, BESS helps optimize the integration of renewable energy into the electrical grid and promotes a more resilient and sustainable energy infrastructure.

6.6.2 Voltage dip detection control in grid side converter

Whenever a dynamic occur in power system near grid, Grid side converter have a specific control which is normally off but it will operate whenever operating conditions deviate from standard values. Whenever a voltage deviation detected this controller plays its role to support in a reactive mode to stabilize the deviation issue. Table 6.1 shows this controller reaction under different conditions

Condition	V_{rms}^{pu}	V_{error}	Controller Reaction
Normal operation	≈ 1.0	≈ 0	Maintain output
Voltage sag (LVRT)	< 1.0	yes	Inject reactive power (Q)
Voltage recovery	$\rightarrow 1.0$	$\rightarrow 0$	Return to steady state

Table 6.1: Controller behavior under different voltage conditions

This controller follows these conditions and operate step wise starting from voltage dip detection then voltage controller and at end reactive power controller to generate new I_q reactive current reference as shown in figure 6.4

6 Enhancement in dynamics and LVRT behavior through battery energy storage system integration to the wind power system

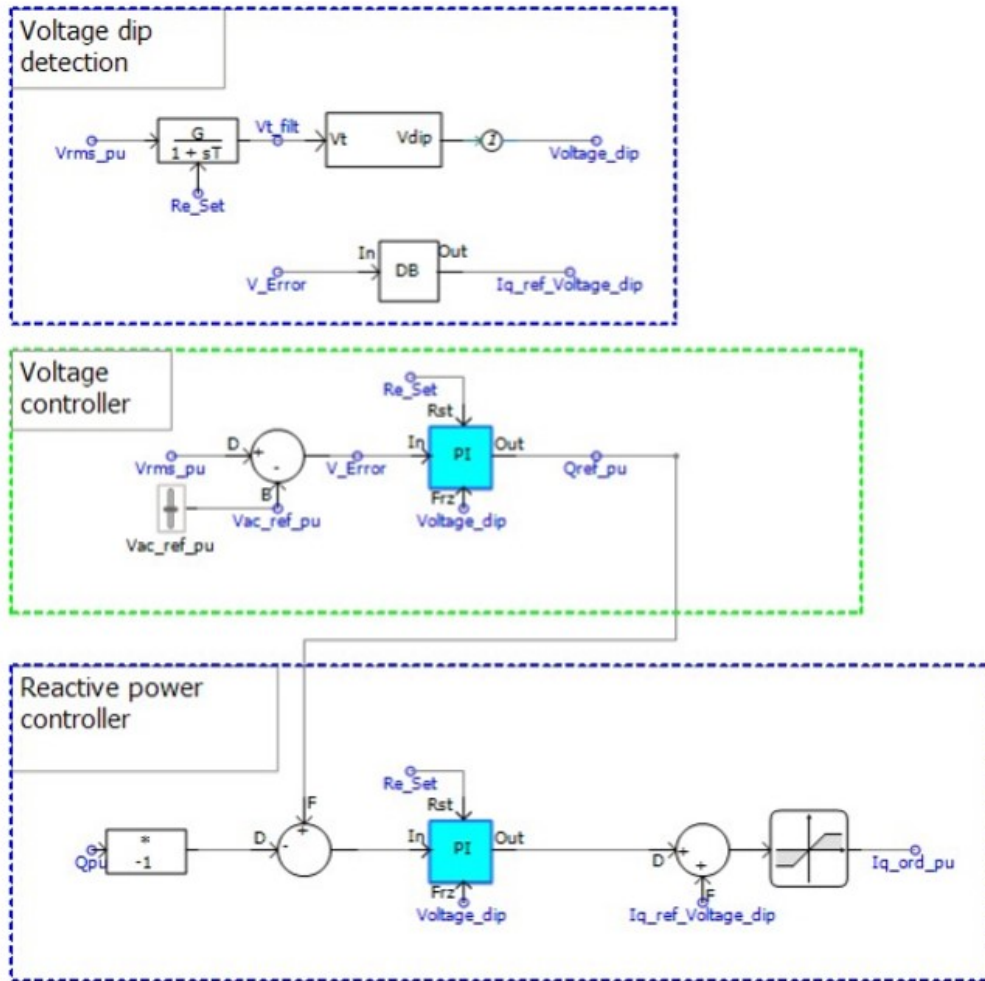


Figure 6.4: Grid side converter LVRT control structure

6.7 Dynamics case study with battery circuit connected at the DC-link location

The research aims to investigate the understanding of ride-through capability in wind turbines and propose methodologies for enhancing this capability using battery energy systems, considering the dynamic nature of grid conditions and the evolving landscape of renewable energy integration. Voltage Source Converters (VSCs) have become a ubiquitous component in renewable energy generation systems, playing a vital role in facilitating the integration of renewable resources into power systems. They serve as interface converters, allowing renewable energy sources to connect to the electrical grid by converting the variable output of these sources

6.7 Dynamics case study with battery circuit connected at the DC-link location

into stable and grid-compatible AC power. Wind turbines equipped with full-scale VSCs are commonly referred to as Type-IV wind turbines. These turbines feature advanced power electronics that allow for precise control of power output and grid interaction. Type-IV wind turbines offer advantages such as improved grid stability, enhanced fault ride-through capability, and increased flexibility in power generation. SCR reflects the grid's ability to withstand faults and disturbances, with higher SCR values indicating greater grid strength and stability.

In the following approach, the LVRT is achieved by integrating a battery energy storage system at the DC-link of a Wind power converter system. The type-IV WT is more commonly used because PMSG has the capability to self-excite, resulting in a high power factor and improved efficiency. Type-IV also deploys full-scale VSCs for complete generated power conditioning. However, the main drawback of a VSCs is that, as all electrical current flows through it, which can cause protection concerns during transient events. This also leads to a rise in the DC link voltage. In the following section, the LVRT is achieved by adding a battery at the DC link of a WT. During LVRT operation, the proposed method utilizes the BESS to absorb any power imbalances within the back-to-back converters, effectively regulating the DC-link voltage.

6 Enhancement in dynamics and LVRT behavior through battery energy storage system integration to the wind power system

- **Case 1: Strong grid SCR=10 LVRT with battery system at DC-link**

In this case, A strong grid with a rating of SCR=10 is taken into account. The simulation is run and fault dynamics have been observed with battery system inclusion.

The impact of the LLG fault on the simulation model is analyzed and LVRT response through the integration of the battery system at DC-link has been investigated. The voltage drop can be visualized in figure 6.5.

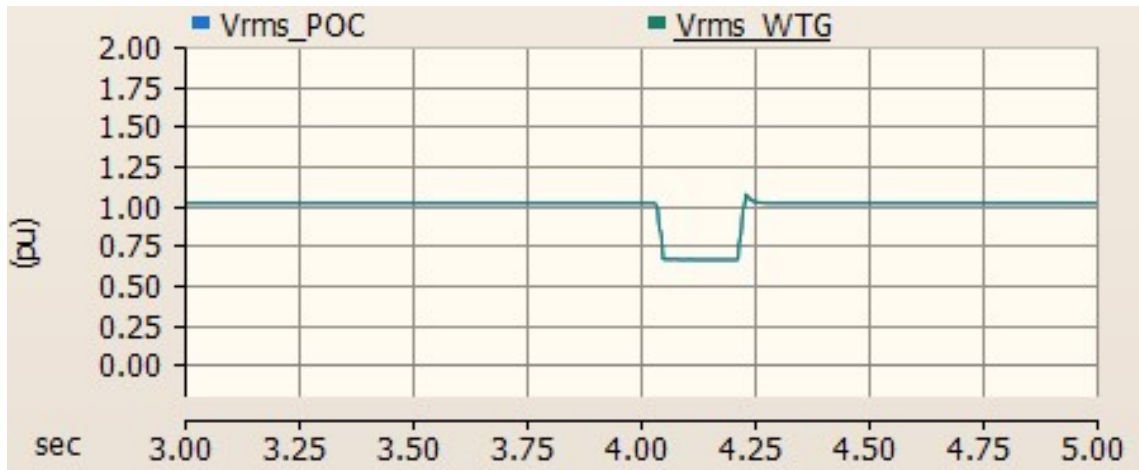


Figure 6.5: Impact of LLG fault in strong grid SCR=10

As the system is strong enough so it can come back to normal value in a very short interval of time after fault happening. But still for this short time interval DC link overshoot problem arises which should be overcome through BESS

6.7 Dynamics case study with battery circuit connected at the DC-link location

The battery system helps to improve the stability concerns during dynamics which can be seen in figure 6.6.

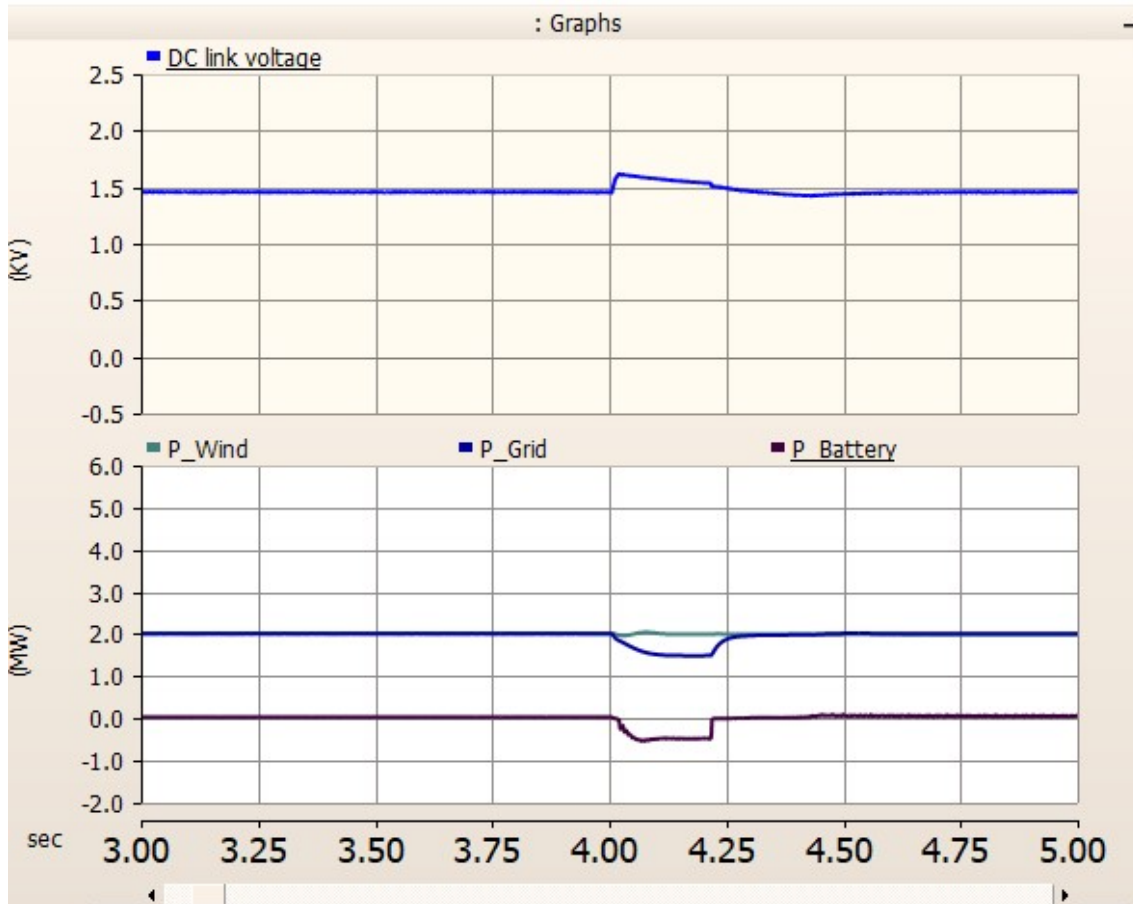


Figure 6.6: BESS response during DC link overshoot fault scenario for grid SCR=10

- **Case 2: Weak grid LVRT with battery system at DC-link**

In this case, investigation is done for weak grid scenario in a type-IV wind turbine with a battery connected at the DC-link. The weak grid was analysed for SCR=3. The calculation for the short circuit ratio is as follows in 6.2

$$SCR = \frac{23KV^2}{88\Omega \cdot 2MW} = 3 \quad (6.2)$$

For the weak grid with SCR value 3, Under a two-phase fault, it appeared in figure 6.7 that the voltage at grid side fluctuatingly dropped significantly and reactive power

6 Enhancement in dynamics and LVRT behavior through battery energy storage system integration to the wind power system

should be provided for proper LVRT, which will be provided through GSC as shown in figure 6.8

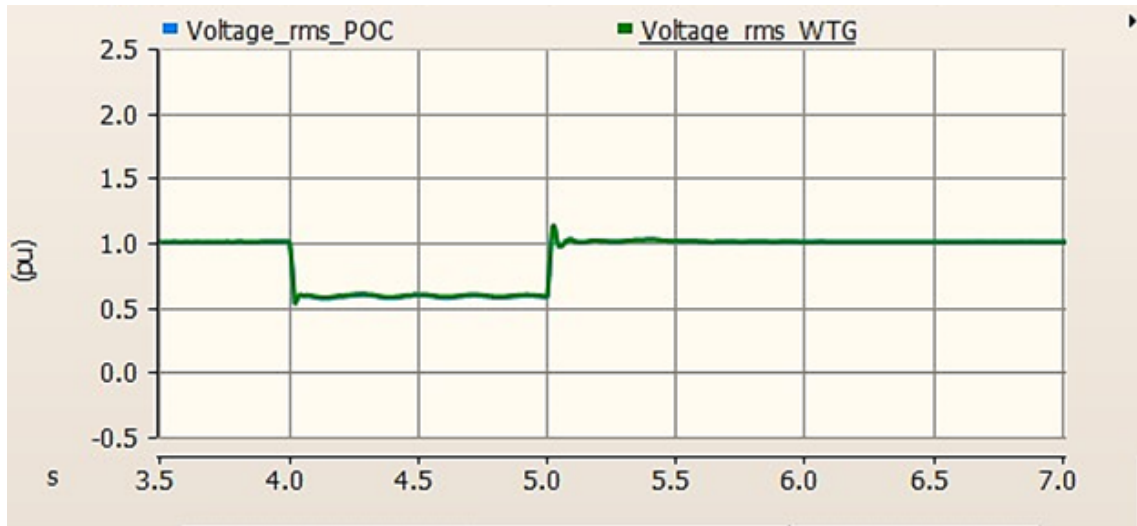


Figure 6.7: Impact of LLG fault in weak grid SCR=3



Figure 6.8: Reactive power compensation through GSC for weak grid SCR=3

6.7 Dynamics case study with battery circuit connected at the DC-link location

With the addition of battery storage at the DC-link point of type-IV WT, as shown in figure 6.9, During LVRT operation, the proposed method utilizes the BESS to absorb any power imbalances within the back-to-back converters, effectively regulating the DC- link voltage

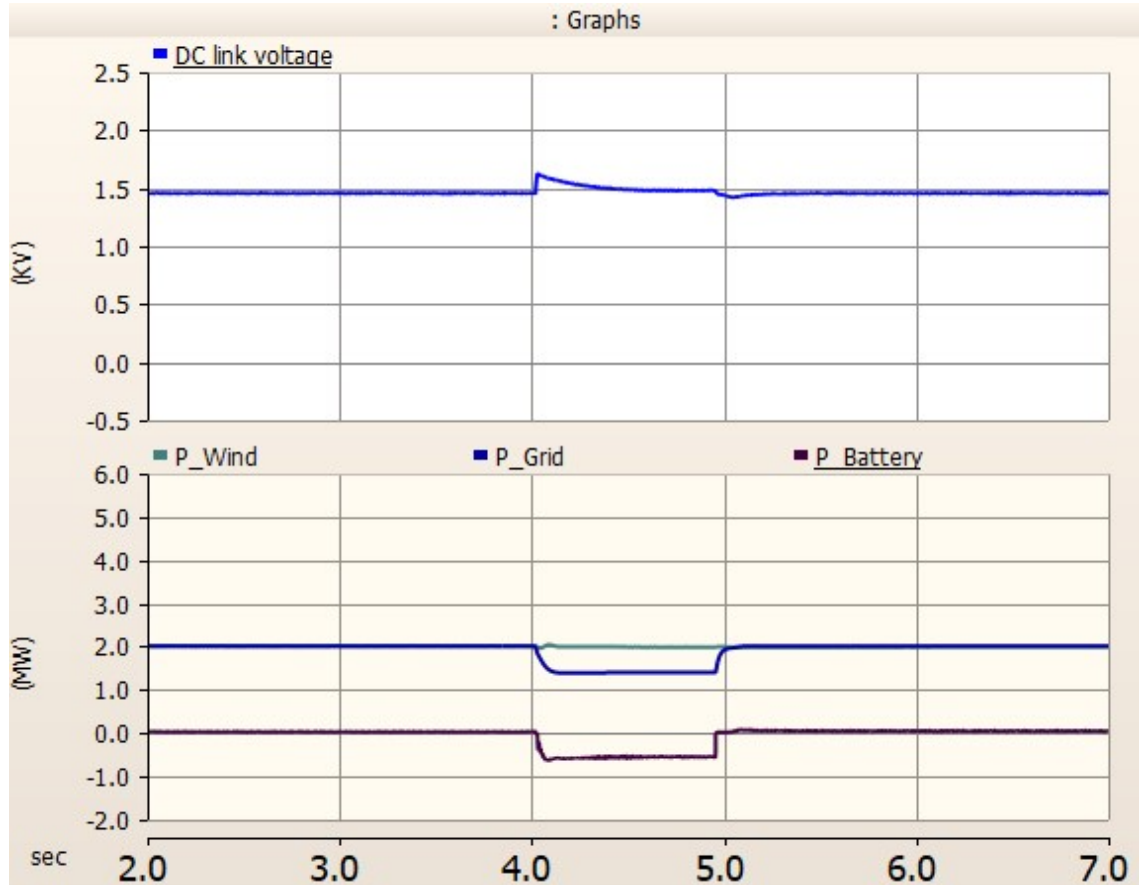


Figure 6.9: BESS response during DC link overshoot fault scenario for grid SCR=3

- **Case 3:Very weak grid LVRT with battery system at DC-link**

In this case, investigation is done for very weak grid scenario in a type-IV wind turbine with a battery connected at the DC-link. The grid was analysed for SCR=2. The calculation for the short circuit ratio is as follows in 6.2

$$SCR = \frac{23KV^2}{130\Omega \cdot 2MW} = 2 \quad (6.3)$$

For the very weak grid with SCR value around 2, Under a two-phase fault, it appeared in figure 6.10 that the voltage at grid side fluctuatingly dropped significantly and reactive power should be provided for proper LVRT, but due to limitation

6 Enhancement in dynamics and LVRT behavior through battery energy storage system integration to the wind power system

of GSC ratings for very weak grid there is no proper reactive power compensation available so voltage become unstable

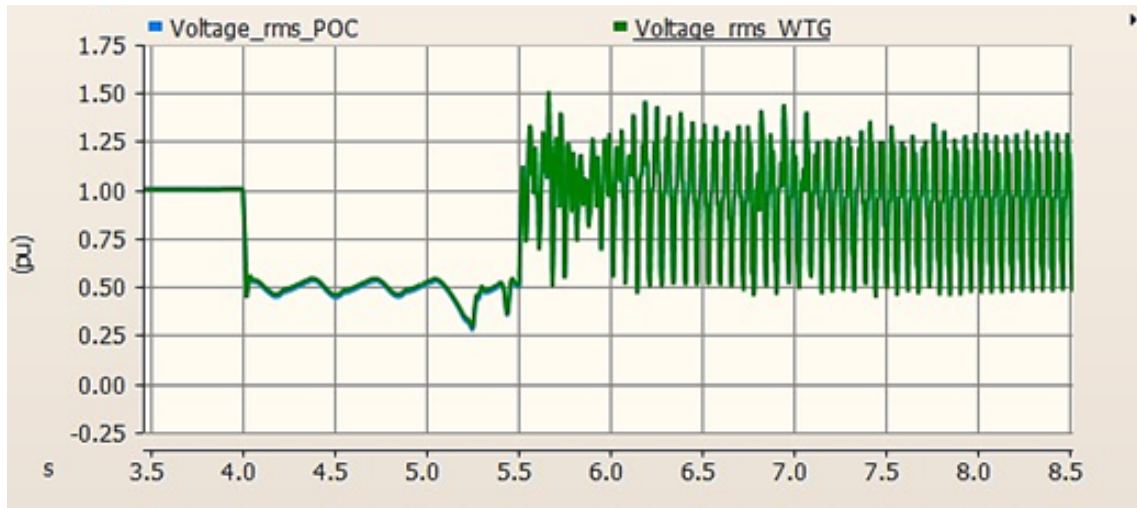


Figure 6.10: Impact of LLG fault in very weak grid SCR=2

so DC-link integrated BESS is best suitable to utilize until grid side converter ratings allow to provide voltage ride through, and for very weak grid dynamics best solution is to install a BESS near POC which can solve this problem and provide reactive power support to stabilize the system voltage for very weak grid dynamics.

6.7 Dynamics case study with battery circuit connected at the DC-link location

Summarized in this research work, PSCAD simulation-based investigation was carried out to validate the existing low voltage ride-through (LVRT) capability of permanent magnet synchronous generator (PMSG) wind turbine. For this approach a battery energy storage system (BESS) at the DC-link location was integrated between full-scale back-to-back converters (VSCs) of a Type-IV PMSG model. From the simulation results, it is established that integrating a battery energy system at DC link with a wind energy system can significantly strengthen grids during faulty conditions but until grid side converter ratings allowed. The proposed ideas can readily be extended to real-life power systems with automated testing features.

7 Conclusions And Perspectives

This research work presented a PSCAD model for the integration of a battery energy storage system (BESS) at the DC-link of a Type-4 full converter wind turbine. The benefits of integrating BESS at the DC-link of the wind power system are that this topology can provide smooth power during on-peak demand and can save excess power from the wind side during off-peak demand and can provide economical advantages regarding unit prices of power delivery. Peak shaving capability improve grid interaction and reduces demand spikes and provide economic power delivery. The design of the battery system will be such that it can be easily installed on a rack inside the tower. The designed system simulated for different set point wind speeds as well as time series wind data and grid set point power demand.

This concludes that BESS can be used as a secondary power source in order to provide constant power to the grid when the wind-generated power is less than the required grid power due to the fluctuating nature of the wind. On the other hand, BESS can save the excess power from the wind when the grid demand is low. This has been achieved by designing a control system for power management by keeping the DC-link voltage stable at a base value keeping the SOC of the BESS into account. BESS has been selected as a cost-effective power storage method. This can even generate new revenue streams as it allows energy arbitrage or directly reduce your electricity bill via peak shaving. The designed system is validated for different case scenarios for wind speed and grid power demand and the results are presented. The control logic continually monitors what the grid needs and how that required power can be transferred from the BESS. This controller sends an input signal to either charge or discharge the battery depending on the control logic requirement and SOC of the battery system.

A wind turbine with integrated storage can supply additional power without reducing the overall energy production. With an increasing portion of renewable electrical power, the new power plants also have to contribute their share to the system stability.

Also, the ride-through behavior under different disturbance scenarios has been analyzed and implemented by including additional control topologies. The investigation was carried out to enhance the existing voltage ride-through capability of the permanent magnet synchronous generator (PMSG).

7 Conclusions And Perspectives

Initially, faults were subjected in different grid conditions. The transient response of faults was observed with the inclusion of battery system in operation. From the simulation results, it is established that integrating a battery energy system with a wind energy system can significantly strengthen dynamic scenarios. This topology improve Low Voltage Ride Through (LVRT) by diverting excess energy into battery charging instead of dumping it in resistor during dynamics DC link overshoot scenarios.

This research makes a critical contribution to the renewable energy and power storage sectors by providing a detailed simulation model and addressing technical challenges related to grid integration. The addition of supercapacitors to BESS in a multi-source converter scheme represents an innovative approach to enhancing the stability, reliability, and efficiency of modern power grids. This work is poised to influence future developments in renewable energy integration and energy storage technology.

Suggested future recommendations are

- Hardware in loop (HIL) implementation for real-world validation
- Machine learning algorithm implementation to predict load demand and wind production
- Collaborate with utilities or microgrids to assess performance under actual operating conditions
- Evaluate the performance of hybrid storage (battery + supercapacitor+Hydrogen) to manage fast transients and long-term energy requirements effectively

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Declaration of Authorship

I, Habib Ur Rehman hereby declare that the thesis titled “Modelling and analysis of battery energy storage integrated wind power system with multi-source converter using software PSCAD.” has been written by me under the guidance of my supervisor. All the sources of information and aid have been acknowledged to the best of my knowledge. This thesis has not been submitted previously for any other qualification at any other universities or institutions.

Erlangen, 18.07.2025

Habib Ur Rehman

A handwritten signature in blue ink that reads "Habib" followed by a stylized flourish.