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Electrical

Virtual inertia to the AC Microgrid to improving the ROCOF and frequency Nadir in a Hybrid AC/DC Microgrid

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Acknowledgements

The thesis marks the complete of the master’s degree in electrical power engineering at UiT Narvik electrical department. The purpose of this thesis implement of the virtual inertia to the AC Microgrid to improving the ROCOF and frequency Nadir. This project will also Matlab simulation and compare ROCOF and frequency Nadir with virtual inertia and without virtual inertia.

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-Dan Bahadur Shrestha Newar.

Abstract

To move the global energy away from fossil fuels towards renewable energy leads toward a more complex grid, after experiencing a reduction of inertia when integrating large renewable energy sources (RES). With an increased pace of RES penetration into the grid and along a growing demand of electrical power, the challenge to maintain the system frequency as close as possible to the nominal range increase.

The RES are limited by wind condition and daylight to provide an energy momentum into the transmission or distribution grid. Therefore, the utilization of virtual inertia to improve the Rate Of Change Of Frequency (ROCOF) and the minimum value of frequency reached during the transient period (frequency Nadir) is an addressed necessity to solve the inertia issue.

Giga Watt projects for solar and wind energy are already built, with several and even larger are both planned and built at the moment, which have resulted in an even higher attention and concern to the transmission lines, distribution grid and the power stability.

Main present global source of electricity production are heat generated, which during phasing out fossil also causes the loss of rotating inertia. This means the issue is and will grow globally in all the parts of the power networks.

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Abbreviations

AC	Alternating current
DC	Direct current
ESS	Energy storage system
HMG	Hybrid microgrid
IC	Interlinking converter
ROCOF	Rate of change of frequency
DER	Distributed energy resources
SG	Synchronous generator
DG	Distributed generator
VSG	Virtual synchronous generator
RP	Renewable power
VI	Virtual inertia
PLL	Phase locked loop
FCR	Frequency containment reserve
FRR	Frequency restoration reserve

MPPT	Maximum power point tracking
BOS	Balance of system
MPP	Maximum power point
DFIG	Doubly fed induction generator
SOC	State of charge
VIC	Virtual inertia control
WTG	Wind turbine generator
PV	Photovoltaic
LPF	Low pass filter

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1 Project Description

Environmental concerns are increasing day by day due to global warming. Simultaneously the power requirement is continuously growing. To resolve the above issue mentioned, efficient renewable energy generation and utilization are needed. Therefore, the concept of AC Microgrid and DC Microgrid is widely used to integrate renewable energy resources (RESs). Additionally, a hybrid microgrid (HMG) is used to reduce the conversion loss from DC to AC and vice-versa. The basic concept of the HMG has been introduced in [1]. In HMG, AC and DC sections are interconnected using an interlinking converter (IC). The control of the IC plays a vital role in maintaining power sharing between AC and DC sections. Lack of inertia is one of the major issues for the stability of HMGs. Hence, a detailed study is needed to investigate the relevance of this inertia in the operation, control, and stability of the HMG. In literature, many controllers to deliver virtual inertia (for example the inertia provided with the energy storages in PVs integrated system) to the system are developed. They mostly mimic synchronous generators by delivering an active power response proportional to the rate of change of frequency (ROCOF).

1.1 Project Assignment

The thesis focuses on the development and analysis of a hybrid AC/DC Microgrid (HMG) with the incorporation of virtual inertia to enhance stability. As environmental concerns escalate due to global warming, there is an increasing need for efficient renewable energy generation and utilization. The HMG integrates AC and DC sections, interconnected through an interlinking converter (IC), aiming to mitigate conversion losses and improve overall system performance.

1.1.1 Problem Analysis

A critical challenge in HMGs is the lack of inertia, impacting their stability. To mitigate this issue, the thesis conducts an in-depth study to investigate the relevance of inertia in the operation, control, and stability of HMGs. Existing literature showcases various controllers designed to deliver virtual inertia, drawing inspiration from synchronous generators. The focus is on implementing virtual inertia in the AC Microgrid to enhance Rate of Change of Frequency (ROCOF) and frequency Nadir, crucial parameters for stable microgrid operation.

1.1.2 Problem Formulation/Objectives

The main goal of the project is to enhance the stability of the Hybrid AC/DC Microgrid by introducing virtual inertia to the AC section.

This project aims to contribute valuable insights into enhancing the stability of Hybrid Microgrids, aligning with the broader objective of promoting sustainable and efficient energy solutions in the face of global environmental challenges.

2 Introduction

A microgrid is a localized and autonomous energy system designed to serve specific areas such as energy hubs, campuses, hospitals, or neighbourhoods. It incorporates various distributed energy resources (DERs) such as solar panels, wind turbines, generators, and often includes energy storage and electric vehicle charging stations. One of its defining features is its ability to generate energy in close proximity to its consumers, reducing energy loss during transmission. Microgrids can operate independently by disconnecting from the main grid during outages or emergencies, ensuring a continuous power supply to consumers and avoiding cascading failures. A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. It can connect and disconnect from the grid to enable it to operate in grid-connected or island-mode [2].These systems are intelligently managed by a microgrid controller, orchestrating resources like generators and batteries to optimize energy usage autonomously. Unlike simple distributed energy systems, a microgrid operates 24/7, providing continuous power even during grid failures. The Department of Energy defines a microgrid as a single controllable entity within defined electrical boundaries. As the demand for resilient and efficient energy solutions grows, the global microgrid market is expected to reach a significant capacity of 19,888.8 MW by 2028, with North America and Asia Pacific emerging as key growth centers. Microgrids play a crucial role in enhancing energy reliability, reducing transmission losses, and contributing to a more sustainable and resilient energy infrastructure [3]. Basically there are three types of microgrids: 1. Ac microgrids 2. Dc microgrids and 3. AC/DC hybrid microgrids. In this project we are discussing about AC/DC hybrid microgrids and initiate to propose the virtual inertia to the AC Microgrid to improving the ROCOF and frequency Nadir. The integration of renewable energy resources (RESs) in power systems has led to the prominence of Hybrid AC/DC Microgrids (HMGs) as a versatile solution. HMGs leverage both Alternating Current (AC) and Direct Current (DC) technologies, interconnected by an interlinking converter (IC), to optimize energy flow and reduce conversion losses . However, the stability of HMGs is a critical concern due to the lack of mechanical inertia, traditionally provided by synchronous generators in conventional power systems [4]. Virtual inertia has emerged as a promising control strategy to address stability issues in microgrids lacking physical inertia. Literature suggests that virtual inertia controllers mimic the behaviour of synchronous generators by responding actively to the Rate of Change of Frequency (ROCOF) . This approach enhances grid stability by providing rapid and dynamic power response during disturbances, thereby improving the system's ability to maintain frequency within acceptable limits [5]. The absence of inertia in HMGs can result in challenges such as increased frequency deviations and prolonged transient responses. Research by Zhang et al. underscores the crucial role of inertia in stabilizing microgrids, highlighting the need for innovative solutions to emulate this stabilizing effect [6].

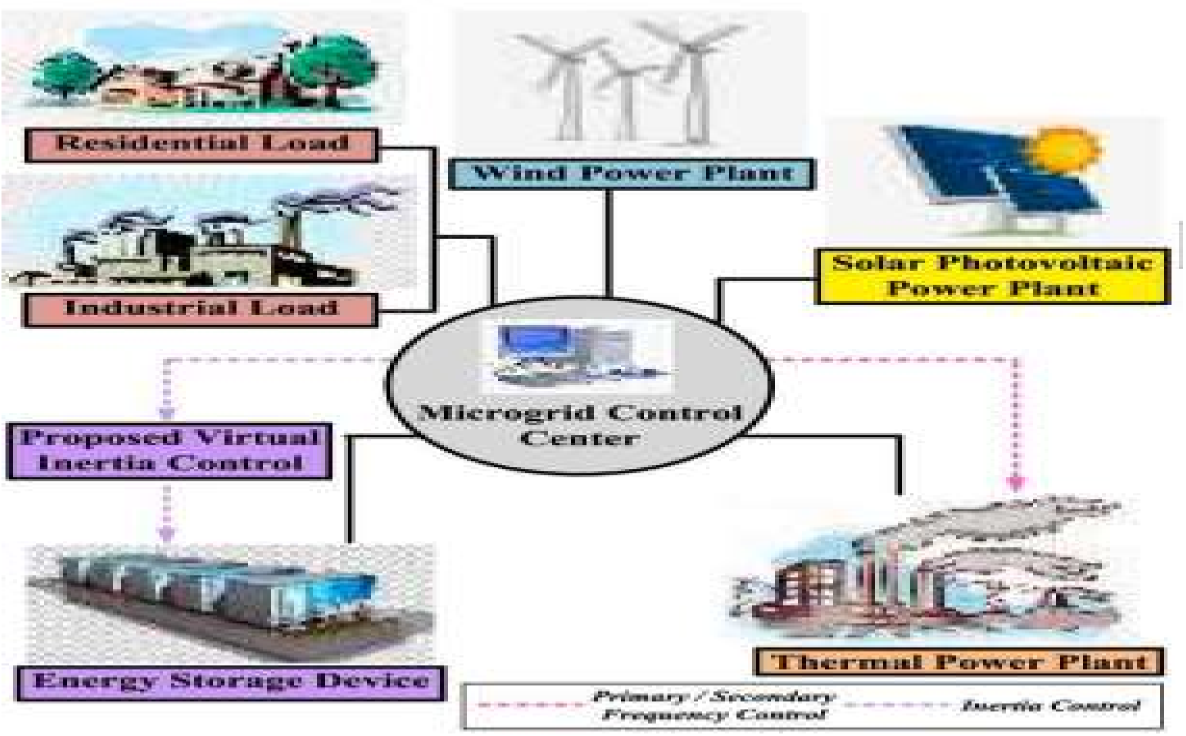

Figure 1 Microgrid model

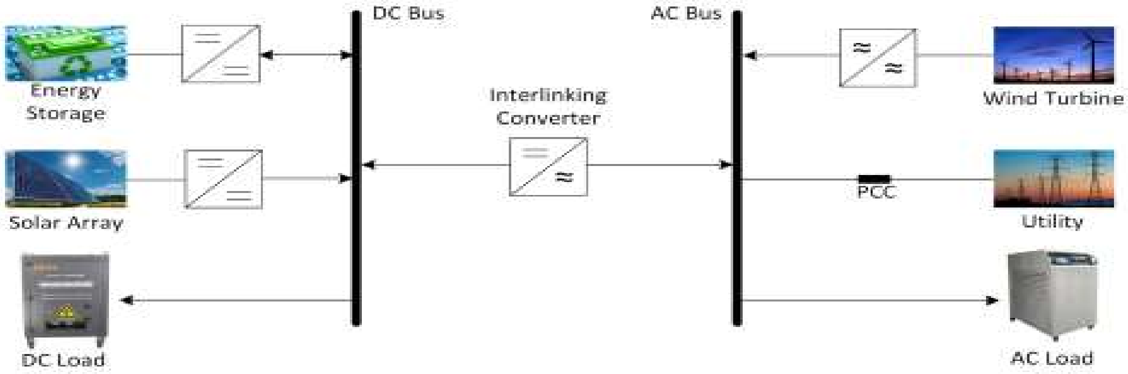

Figure 2 Hybrid microgrid

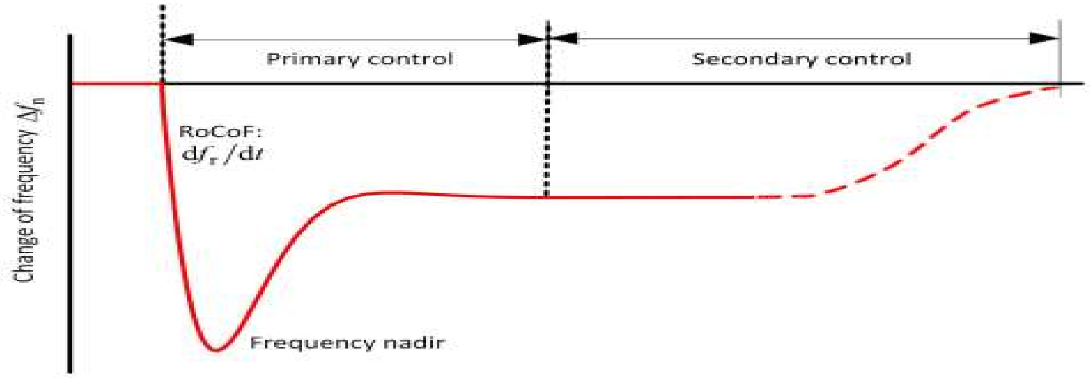

Figure 3 Frequency response to a large generation outage.

3 Present Design and Configuration of Power Transmission and Distribution

The transmission systems are in some countries like the Nordic countries, mainly radial networks, or like Central Europe with a more meshed network where the congestion are less bound to “bottlenecks” in between different areas. The networks are powered by synchronous generators (SG), and by this also a rotating inertia that are initiated to contribute to balance the electric power system. Besides Norway and Sweden, the SG are mainly fed by thermal turbines, which are gas or steam turbines, fired by oil and gas, or coal or nuclear.

For India the main electricity contribution is generated by coal power plants, with a COP21-committed plan of 40% non-fossil installed by 2030, which was already achieved now in 2023 [7]. The bulk power transmission from both outer ends and section of region to region are arranged through bi-directional and back-to-back HVDC interconnections.

India does not have a single unified grid but consists of five regional AC-grids referred to as “Regional Power Committees” or “Regional Power Systems”. The HVDC-links allows for transferring surplus power from one region to another, to balance the power demand and supply. The interconnection of the five regional grids establishes a nationwide power network, commonly known as the “National Grid”, shown in figure 4.

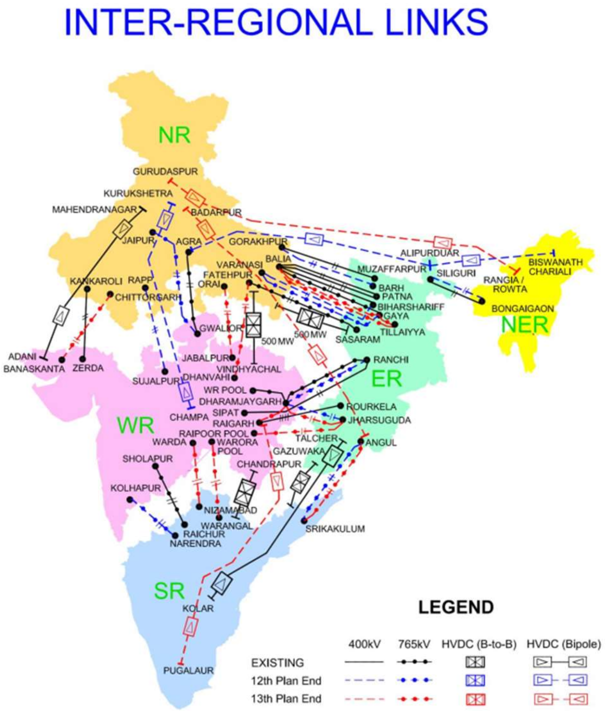

Figure 4 shows a map of the Indian "National Grid" and the interconnected five regions.

Figure from : https://cevgroup.org/electrical-power-sytem-the-indian-frame/

4 Literature Review

Zhang et al. [8] introduces a novel approach to enhance the stability of hybrid AC/DC microgrids by incorporating bidirectional virtual inertia support. By introducing virtual inertia to both AC and DC subgrids, the proposed method effectively mitigates voltage and frequency fluctuations, thus reducing the risk of system instability and potential blackouts. Experimental validation demonstrates significant improvements in frequency nadir, rate-of-change-of-frequency (ROCOF), and DC bus voltage deviation, highlighting the efficacy of bidirectional virtual inertia support. The approach, achieved through modifications to the bidirectional interlinking converter control, offers a promising solution for enhancing overall system inertia and stability in hybrid microgrid configurations.

Bevrani et al. [9] underscores the crucial role of inverter-based virtual inertia in improving grid frequency regulation and stability amidst the integration of distributed generators (DGs) utilizing renewable energy sources (RESs). By addressing the reduction in system inertia due to increased penetration of RES-based DGs, the study examines the dynamics of frequency deviations resulting from the parallel operation of the grid and virtual synchronous generators (VSGs). The theoretical analysis confirms the stabilization effects provided by VSGs, laying the groundwork for enhancing overall frequency control schemes in power grids through the addition of inertia control loops. This research contributes valuable insights into the dynamic impacts of high DG and RES penetration on power networks and proposes relevant ideas for improving frequency stability and control performance.

Miura et al. [10] delves into the critical issue of grid stability amidst the increasing penetration of distributed generators (DGs) with low inertia and damping properties. It highlights the role of virtual synchronous generators (VSGs) as a solution to enhance grid stability by providing virtual inertia through short-term energy storage and advanced control mechanisms. The review covers the fundamentals and main concepts of VSGs, emphasizing their significance in supporting power grid control. A VSG-based frequency control scheme is discussed, focusing on the potential of VSGs in regulating grid frequency. The paper presents the most important VSG topologies and surveys recent achievements in this area. It concludes by addressing key issues, technical challenges, and outlining future research directions and perspectives.

Overall, this paper provides valuable insights into the role of VSGs in addressing the challenges posed by low inertia and damping effects in grids with high DG penetration, offering a pathway towards improved grid stability and dynamic performance.

Tamrakar et al. [11] presented a comprehensive highlight on virtual inertia systems within modern power systems undergoing high renewable energy penetration. It addresses the shift from synchronous machine-based systems to inverter-dominated ones and the associated challenges in maintaining frequency stability. By comparing and classifying various virtual inertia topologies, the paper demonstrates how these systems can emulate the dynamics of synchronous generators to enhance grid stability.

This paper highlights the fundamental objective of virtual inertia systems: providing dynamic frequency response through power electronic converters. It categorizes topologies based on system control architecture and the desired level of replication of synchronous generator behaviour.

Furthermore, the paper explores the second generation of virtual inertia systems, focusing on optimization techniques to improve energy storage system (ESS) lifetime, reduce curtailment of renewable energy sources, and enhance overall stability and dynamics.

Challenges and future research directions, including inertia estimation, control improvements, market integration, and ESS utilization, are also discussed. Overall, this review provides valuable insights into the current state-of-the-art and potential advancements in virtual inertia systems for modern power grids with high renewable energy penetration.

Pawan et al. [12] investigates the operation of an interlinking converter within a hybrid microgrid system, employing both primary and secondary control strategies. The primary control utilizes droop control for the AC and DC buses, while secondary control is employed to restore frequency and voltage levels in their respective sections. The integration of hybrid droop control, along with a low pass filter in the interlinking converter, aids in balancing power distribution between the AC and DC sections, ensuring smoother transitions during load changes. The study suggests viewing the hybrid microgrid as akin to a two-area power system network, with the AC and DC sections acting as separate areas interconnected by the interlinking converter, resembling a tie line. Simulation results confirm the effectiveness of the proposed control strategies and highlight the feasibility of analyzing the hybrid microgrid as a two-area system, offering valuable insights for designing and optimizing such systems.

Rajasi et al. [13] addresses the challenge of frequency instability in microgrids with high renewable power (RP) penetration and low inertia. It proposes a Virtual Inertia (VI) control system optimized using Genetic Algorithms (GA) to emulate inertia and damping effects, alongside an energy storage device, for improved frequency regulation. The study considers a dynamic microgrid model with thermal, wind, and solar power sources, focusing on controlling Rate of Change of Frequency (ROCOF) and frequency responses under various load and weather conditions. Mathematical analyses underscore the benefits of adding VI control to steady-state stability and system sensitivity. Comparisons with existing VI control methods demonstrate superior performance, showcasing reduced frequency deviation, undershoots, zero steady-state error, and shorter settling times. The inclusion and optimization of damping and inertia components in the VI system significantly enhance dynamic response, affirming the effectiveness of the proposed technique in mitigating frequency regulation challenges in low-inertia microgrids with high RP penetration.

Domonique et al. [14] addresses the pressing issue of declining system inertia in power grids due to increased renewable energy integration, proposing a methodology for sizing energy storage systems (ESS) to provide virtual inertia support. By considering local frequency dynamics and fault locations, the methodology aims to distribute inertia provision effectively, minimizing overall power and energy requirements for ESS. Validation using the IEEE 9-bus system and a case study of the island of Santiago, Cape Verde, demonstrate the effectiveness of the approach in improving frequency response and ensuring system stability. The paper suggests further integration of the methodology into optimal ESS sizing frameworks for market participation and adjustment of virtual inertia gain under different operating conditions to optimize ESS energy usage. Overall, the proposed method presents a promising solution for system operators to enhance grid reliability based on frequency stability criteria amidst rising renewable energy penetration.

Harold et al. [15] introduced a predictive approach for estimating the timing of frequency nadirs in power grids with extremely low inertia, aiming to preemptively address system protection triggers and prevent unnecessary blackouts. The method employs a Nonlinear Auto-Regressive (NAR) model based on an Artificial Neural Network (ANN) to forecast frequency nadirs. Simulations conducted under various scenarios of inertia reduction demonstrate the adaptability of the approach across different prediction horizons. Results indicate that using a forecast input data length of 7.5% of the time series yields the most accurate predictions, requiring forecasting to occur 250 ms before the frequency nadir for optimal performance. While computational costs vary among scenarios, the models generally exhibit manageable computation times, paving the way for potential real-time implementation pending further study. Overall, the paper highlights the potential value of coupling frequency nadir estimation with predictive controls to enhance grid stability in the face of declining system inertia.

Sakimoto et al. [16] addressed the growing instability in power grids due to the increasing capacity of distributed generators, particularly those connected via inverters controlled by Phase Locked Loops (PLLs). To mitigate this instability, the concept of Virtual Synchronous Generator (VSG) is introduced, wherein inverters are controlled to mimic the behaviour of synchronous generators, thereby enhancing grid stability through virtual inertia. The paper investigates the control scheme of VSG based on the swing equation of a synchronous generator. Numerical simulations demonstrate the ride-through capability of voltage dips and the improvement in grid stability with VSG implementation. Additionally, a new control scheme is proposed to further enhance voltage dip ride-through capacity, with simulation and experimental results validating its effectiveness. Overall, the paper presents a promising solution to address grid instability issues associated with the proliferation of distributed generators.

5 Theory

5.1 Rate of Change of Frequency in Microgrids

The rate at which the power quality of an electric system changes is called the ‘rate-of-change of frequency’ (ROCOF) and is used to assess sub-second control decisions [17]. ROCOF is a key parameter in power system analysis that quantifies the speed at which the electrical frequency of a power system is changing over time. Expressed in hertz per second (Hz/s), ROCOF provides a dynamic measurement of the system's deviation from its nominal frequency, typically 50 or 60 hertz. It is a critical metric for monitoring and assessing the stability of the power grid, as abrupt changes in frequency, as captured by ROCOF, can indicate disturbances, faults, or variations in the balance between generation and consumption. ROCOF is particularly vital for the early detection of system anomalies, enabling rapid response mechanisms to maintain grid stability and prevent cascading failures [18]. Power system frequency and rate-of-change-of-frequency (ROCOF) are important metrics in the context of increasing levels of distributed generation; they are used as inputs to control systems for protection, power balance management, and provision of system inertia of electricity grids [19]. The increasing integration of inverter-based power plants that do not inherently contribute to system inertia, and on the other hand, the disconnection of synchronous generators, leads to the high values of ROCOF in the case of disturbances. Theoretically, the highest system ROCOF, just after the load disturbance occurs, depends on average system inertia and size of disturbance [20]. and can be calculated as follows

$$ROCOF_{t=0+}^{max} = \frac{df}{dt} = \frac{P_k}{2\Sigma_{i=1,i\neq k}^{N} H_i S_i} f_n \qquad (1)$$

Where f_n refers to the standard operating frequency of the power system, typically around 50 or 60 Hertz. P_k represents the magnitude of a disturbance in the power system, measured in megawatts (MW). Hi is the Inertia Constant, Si is the nominal power of the ith generator [MVA]

Improving ROCOF in microgrids is essential for ensuring grid stability, protecting equipment, accommodating renewable energy sources, enhancing resilience, and maintaining compliance with regulatory standards. It contributes to the overall reliability and efficiency of the microgrid, especially in dynamic and changing operating conditions [21].

After a significant disturbance in a power system, the management of frequency is categorized into distinct control strategies: inertial frequency response, Frequency Containment Reserve (FCR), which is a form of primary control, and Frequency Restoration Reserves (FRR), representing secondary control. The inertial response is inherent in the system due to the rotating mass of synchronized machines. This response occurs within seconds, countering frequency deviations resulting from a loss of generation or a load event.

In the event of losing a generating unit in a synchronous system, the frequency drops due to the imbalance between generation and load. Mechanical power transforms into electrical power from the rotating masses, leading to a decline in frequency. During this period, the inertial response from the spinning machines releases or stores kinetic energy, working to minimize the frequency deviation. The overall system frequency response is evident during this time, with system inertia being directly related to the total kinetic energy stored in all rotating masses.

The inertial constant of a specific generator represents the duration that the generator can provide full output power from its stored kinetic energy, typically ranging from 2 to 9 seconds. Once the inertial response stabilizes the frequency, it is further restored to the nominal frequency by the FCR, primarily through governor action, and secondary controllers. FCR operates as a proportional controller, counteracting significant frequency deviations, and its response occurs within seconds (typically less than 30 seconds). However, a steady-state error may persist without additional controls. FRR addresses this steady-state error over time. The entire frequency response, encompassing the control reactions over different time frames, is illustrated in Figure 1 [22].

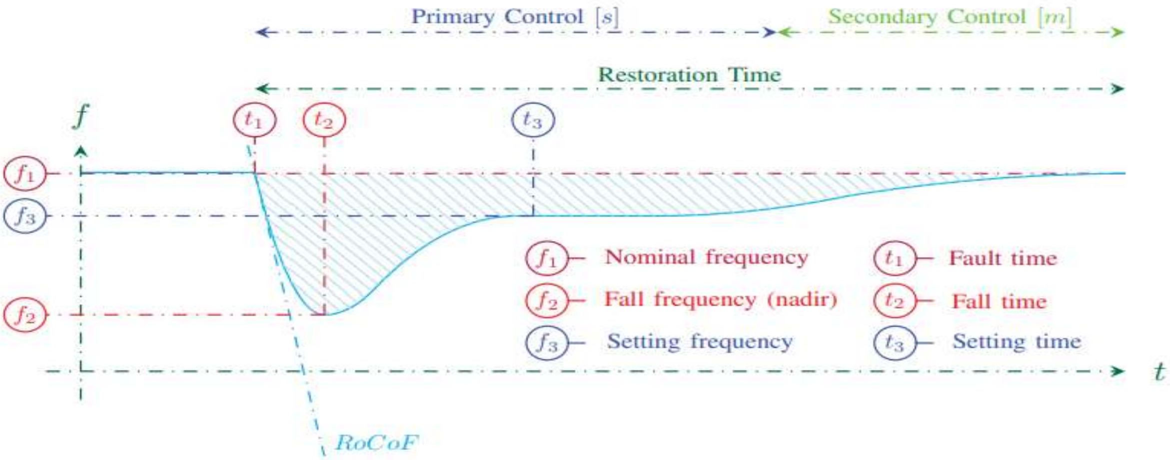

Figure 5 Frequency Response on the power system

5.2 Frequency Nadir

Figure 5 shows the frequency nadir (f_2 is the frequency nadir). The frequency nadir is a significant indicator for the primary frequency response monitoring and control. It is imperative to predict the maximum frequency deviation and the time at which the maximum occurs with high efficiency and accuracy following a major disturbance [23]. Frequency nadir is a critical parameter in microgrids, reflecting the lowest point the system frequency reaches during transient events. The importance of monitoring frequency nadir lies in its direct impact on the stability and resilience of the microgrid. In the face of disturbances like load changes or fluctuations in renewable energy generation, understanding frequency nadir becomes vital for rapid recovery and the prevention of cascading failures. Microgrids, often incorporating renewable sources, benefit from assessing how well they manage frequency under varying energy inputs. Additionally, frequency nadir influences decisions related to load shedding and islanding, ensuring optimal responses to maintain stability. Compliance with regulatory limits for frequency nadir is essential for grid reliability, and understanding this parameter is crucial for the effective operation of energy storage systems within microgrids. Overall, frequency nadir serves as a key metric in ensuring the reliable and resilient operation of microgrids in diverse and dynamic operating conditions [24].

5.3 Virtual Inertia in AC Microgrids

Virtual inertia is a concept in power systems engineering that involves emulating the stabilizing effect of mechanical inertia traditionally provided by rotating mass in synchronous generators. In traditional power systems, synchronous generators, connected to rotating turbines, contribute inertia to the grid. This inertia helps stabilize the grid's frequency by resisting sudden changes in generation or load [25].

As we transition towards power systems heavily reliant on Renewable Energy Sources (RESs), the incorporation of inverter-based RES generation units becomes prevalent. However, these units lack inherent inertia, contributing to a substantial decrease in the overall inertia of the system. The significant presence of these inertia-less inverter-based units poses potential challenges to the stability and operation of the power system. Addressing the impacts of this high share of inverter-based generation units is crucial for ensuring the stability and effective functioning of the future power grid [26, 27, 28].

Addressing the challenges posed by low system inertia and enhancing stability, especially in terms of frequency stability, involves introducing additional inertia into the power system through virtual means without relying on physical rotating mass. This approach is a promising solution, and there exist various topologies to emulate virtual inertia. Despite sharing a fundamental concept, these topologies differ in the level of detail in their implementation. Exploring different virtual inertia emulation strategies provides valuable insights into their nuances [28].

To delve into various topologies for virtual inertia emulation, briefly discuss notable examples and highlight their differences:

1. Synchronous Generator Model-Based Topology:

This category involves emulating virtual inertia using models based on synchronous generators. By mimicking the behaviour of synchronous generators, this topology contributes to enhancing system stability.

2. Swing Equation-Based Topology:

Another approach employs swing equations to emulate virtual inertia. This methodology offers a unique perspective, utilizing mathematical equations to simulate the inertial response within the power system.

3. Frequency-Power Response-Based Topology:

Emphasizing the frequency-power response, this category focuses on emulating virtual inertia through dynamic adjustments in power output. This topology provides a practical means of addressing challenges associated with low system inertia.

Understanding the distinctions between these three main categories of virtual inertia emulation topologies sheds light on the diverse strategies available. Each category brings its own set of advantages, contributing to the overall goal of improving stability in low inertia power systems, especially as renewable energy integration continues to grow.

5.4 Hybrid Microgrid

A hybrid microgrid merges AC and DC microgrids, minimizing power conversion losses and enabling seamless connection of diverse energy sources and loads. However, it presents challenges such as complex coordination control, power quality issues, reliance on sensitive converters, communication needs, and synchronization, impacting technical, operational, protection, and economic aspects [29].

Hybrid microgrids represent a transformative approach to modern energy systems, offering a balance between sustainability, reliability, and economic viability. Continued research and technological advancements in control strategies, energy storage, and renewable technologies will further enhance the capabilities and widespread adoption of hybrid microgrids in the pursuit of a sustainable energy future [30].

The schematic illustration of a hybrid AC-DC microgrid connected to a utility grid shown in Fig.6 reveals a versatile energy system.

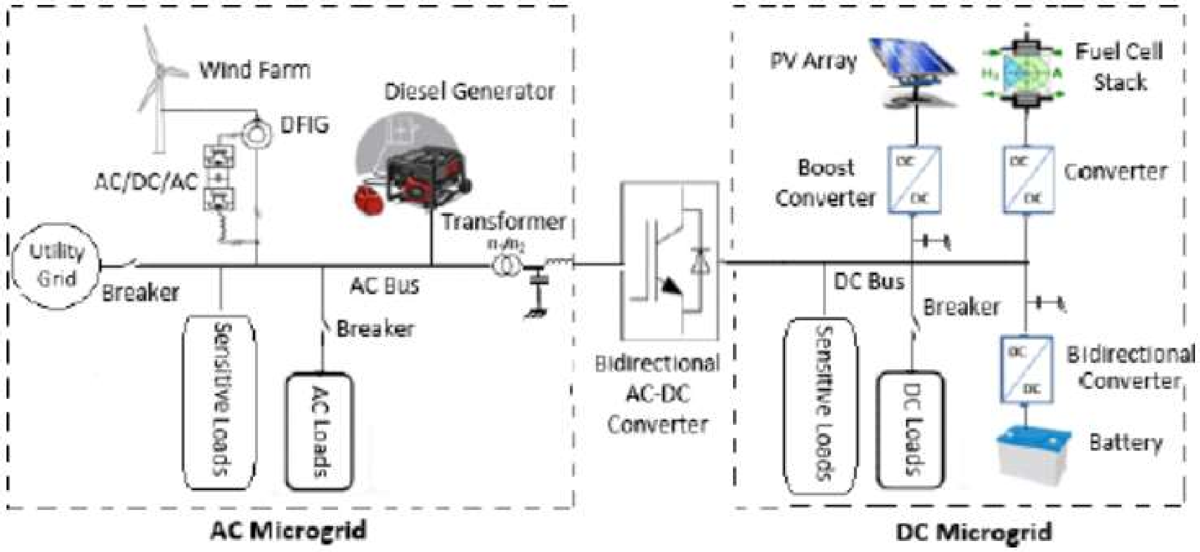

Figure 6 Hybrid Microgrid with BIC

The AC and DC grids interconnect through a bidirectional converter, allowing the hybrid grid to operate in either grid-tied or autonomous mode based on the utility grid's condition. Under normal conditions, the hybrid microgrid functions in grid-tied mode, with surplus power sent to the utility grid and power shortages supplemented by the utility. All generation units optimize power production through Maximum Power Point Tracking (MPPT). During a utility fault, the microgrid seamlessly transitions to Island mode. In this mode, Energy Storage Systems (ESS) play a crucial role in balancing energy between grids and maintaining DC side terminal voltage. The bidirectional converter not only transfers power between AC and DC grids but also provides reference voltage and frequency for the AC grid during Island mode. If generation falls short of demand, non-firm loads may be curtailed, and ESS units operate in discharge mode. Conversely, in excess generation scenarios, ESS units operate in charging mode under off MPPT. Both PV and wind turbine generators can adjust their operation modes based on system requirements, either on MPPT or off MPPT. This adaptive operation ensures efficient and reliable functioning of the hybrid AC-DC microgrid [31].

5.5 Energy Storage System

Energy Storage Systems (ESS) play an important role in effectively managing the generated energy, thereby optimizing power flow within the system. They serve as key elements enabling strategic energy management, particularly by addressing the intermittent nature of renewable energy sources and enhancing system reliability during power supply failures. ESS in the context of hybrid grids function as versatile management tools, offering benefits such as demand-side management, power flow control, load displacement, and frequency regulation. One of the primary advantages of ESS lies in their ability to significantly improve stability, power quality, and supply reliability within the power system across various operational modes. Unlike traditional synchronous generators, ESS possess the unique capability to swiftly adjust power output owing to the characteristics of their power converters. This agility allows them to modulate power without disrupting the overall power flow dynamics of the system, making them indispensable components in modern microgrid configurations. [32]

As stated in reference [33], ESS serve eight main purposes, which are elaborated below.

1. Frequency Regulation
   Frequency regulation within the grid can be effectively achieved through the utilization of Energy Storage Systems (ESS), which help balance the generation and load over extended timeframes.
2. Frequency Control
   Frequency control or response is crucial for maintaining the stability of a power system. When there's a sudden loss of generation or an increase in load, the frequency of the system can drop. To address this, ESS can step in to provide the needed power and stabilize the frequency. ESS can play roles in both primary and secondary frequency control. Primary frequency control acts quickly, lasting only a few seconds, while secondary frequency control provides support over a few minutes.
3. Volt/ VAR Support
   Fluctuations in voltage can be mitigated by utilizing ESS to supply reactive power when voltage is low and absorb reactive power when voltage is high. This capability, known as volt/VAR support, is a critical feature of smart inverters. It enables the seamless integration of high levels of renewable energy into the grid by effectively managing voltage levels.
4. Autonomous Microgrid
   To enhance the reliability and cost-effectiveness of an autonomous microgrid, ESS can be integrated alongside other renewable energy sources. In such microgrid setups, ESS serve various critical functions, including supplying energy during deficits, facilitating black start capabilities, and providing support for voltage and frequency regulation. This multifaceted role of ESS contributes significantly to the overall resilience and efficiency of the microgrid system.
5. Peak Saving

ESS offer versatile solutions for managing energy demand and supply dynamics within the grid. They can provide energy to meet peak load demands or store excess energy generated during peak renewable energy production. Additionally, ESS enable energy time shifting, allowing energy delivery during periods of high electricity prices and charging during low-price intervals.

Moreover, ESS play a crucial role in reducing grid stress by supplying energy during transmission or distribution line congestion. Conversely, they provide the option to defer energy usage during transmission or distribution line upgrades, ensuring efficient grid operation while minimizing disruptions.

6. Power Quality

   Voltage sags or interruptions resulting from faults within the system can cause significant power quality issues. ESS offer a solution by injecting real power for brief intervals, effectively mitigating these problems and enhancing overall power quality.

7. PV Power Smoothing

   The intermittent nature of PV systems can result in fluctuations in output power, leading to brief voltage excursions. ESS offer a solution by smoothing the output power from PV systems for short intervals, effectively mitigating voltage excursion issues.

8. PV Firming

   As an application of ESS, PV firming involves enhancing the power output from PV systems to ensure consistent power supply to the load over a specified timeframe. ESS intervene by delivering power to the load when the output from PV systems falls short of demand or by absorbing excess power from PV systems when their output exceeds demand.

5.6 PV System

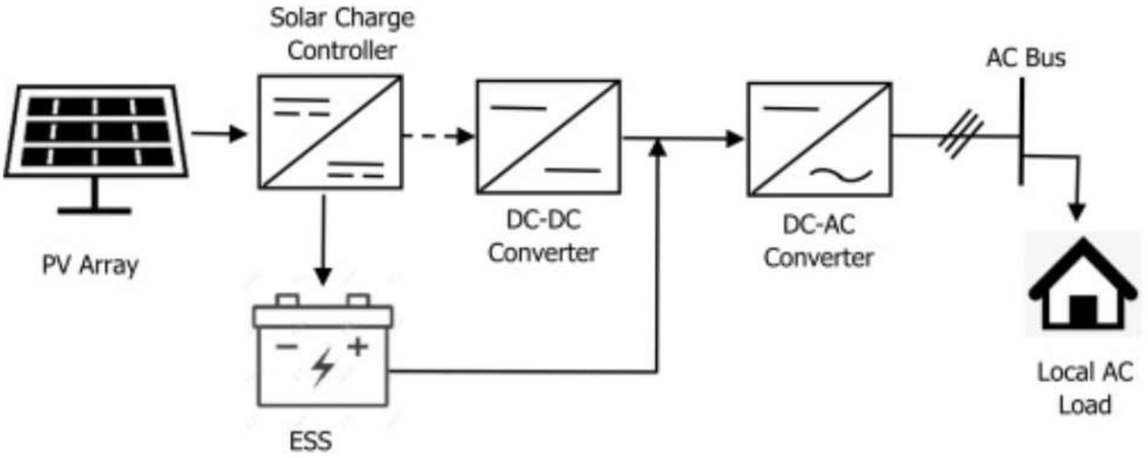

Figure 7 Simple system connected to load

The size of solar PV systems can range widely, from small setups with a few panels to large installations spanning several megawatts that utilize extensive arrays of panels. The figure shown the simple PV system.

Solar PV systems are designed to harness sunlight and convert it into electrical energy using the photovoltaic effect. This phenomenon occurs when semiconductor materials produce voltage and current upon exposure to light, typically achieved through solar cells. These cells, often made from polycrystalline or monocrystalline silicon, can be arranged in series or parallel configurations to meet specific voltage and current requirements. Solar cells are assembled within a metal frame to form a solar module or panel, which is the commercial format for solar PV technology. In these systems, the solar panel captures sunlight and transforms it into electric power, which is initially in DC form. This DC power is then converted to AC by a solar inverter. Additional components might include a solar tracking system to boost efficiency and a battery bank to store the generated electricity. All parts of the system other than the solar panels are collectively known as the balance of system (BOS). [34]

5.7 DC/DC Bi-directional Converter

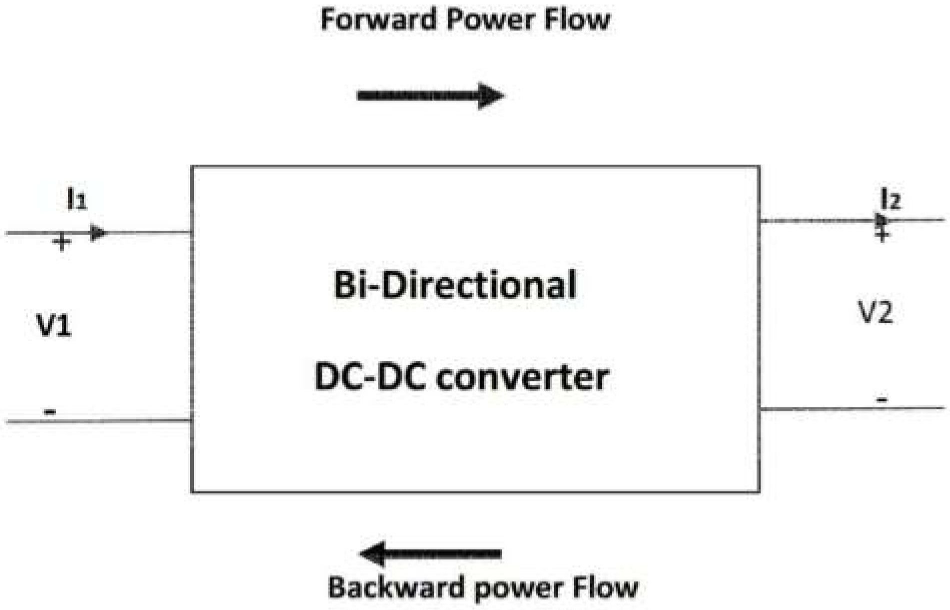

Figure 8 DC-DC bidirectional converter

The Bidirectional DC-DC Converter block represents a converter that steps up or steps down DC voltage from either side of the converter to the other as driven by an attached controller and gate-signal generator. Bidirectional DC-DC converters are useful for switching between energy storage and use, for example, in battery storage system [35].

The bidirectional DC/DC converter, derived from the traditional unidirectional version, facilitates energy transfer in both directions. In today's market, electronic devices heavily rely on stable power supplies. As technology advances, the variety of electronic products expands, underscoring the importance of stable power systems for optimal functioning and safety.

Renewable energy sources like wind and solar power are increasingly utilized in microgrid systems. These systems, consisting of energy storage, power supplies, converters, and loads, offer independent and controllable power solutions. DC microgrid systems, particularly adept at maintaining frequency stability, reactive power regulation, and minimizing AC losses, find applications in data centers, residential areas, and public spaces.

The energy storage system and the bidirectional DC/DC converter are pivotal in DC microgrid setups. A well-designed system enhances micro power supply efficiency. Voltage stability in microgrids hinges on hardware circuits and control methods of bidirectional DC/DC converters, ensuring proper energy flow and grid stability.

Traditional DC converters limit current flow to one direction due to limitations in switching devices like MOSFETs and IGBTs. Although some AC converters facilitate limited bidirectional energy flow using anti-parallel methods, only one converter operates at a time, leading to resource inefficiencies.

To address these challenges, this study advocates for bidirectional DC/DC converters to enhance conversion efficiency by simplifying elements and enabling bidirectional energy flow between AC busbar voltage and energy storage units. These converters offer significant energy savings and environmental benefits, making them critical for future energy-efficient systems [36].

5.8 Bidirectional Interlinking DC-AC Converter

The Interlinking DC-AC converter plays a crucial role in facilitating the bidirectional transfer of power between AC and DC buses in electrical systems. One of its key features is the utilization of a hybrid droop control strategy, which effectively manages both real and reactive power transfer. This control scheme employs a current controller operating within a synchronous reference frame to regulate the power flow. The hybrid droop mechanism, depicted graphically in Fig. 9, is governed by Equation (2), where real power transfer is determined by the difference between the changes in frequency on the AC side and voltage on the DC side. This difference is then scaled by the respective droop gains for frequency and voltage. In essence, this approach enables precise control over the power exchange between the two buses, ensuring efficient operation of the system.

$$P^{ic} = P_0^{ic} - K_{ac}^{ic}(f - f_0) + K_{dc}^{ic}(V^{dc} - V_0^{dc}) \qquad (2)$$

Where P^{ic} is calculated power, P_0^{ic} is reference real power, f is measured frequency, f_0 is reference frequency, V^{dc} is measured DC voltage, V_0^{dc} is reference DC voltage, K_{ac}^{ic} is AC interlinking droop gain and K_{dc}^{ic} is DC interlinking droop gain.

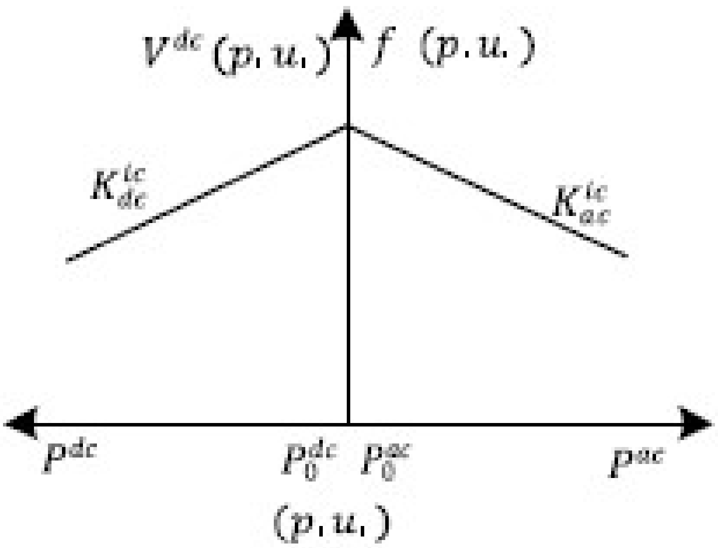

Figure 9 Hybrid droop

To further enhance the accuracy and stability of real power transfer, a low pass filter (LPF) is introduced. Equation (3) illustrates how this LPF filters the calculated power derived from the hybrid droop, thereby smoothing out abrupt changes in load conditions. By adjusting the cutoff frequency of the LPF, the dynamics of the interlinking AC-DC converter can be effectively controlled, ensuring seamless power transfer and maintaining per-unit power balance across the system.

$$P^{ic}_{set} = \frac{w^{ic}_c}{s+w^{ic}_c} P^{ic} \qquad (3)$$

Where P^{ic}_{set} is set real power of IC, P^{ic} is calculated real power IC, w^{ic}_c is IC LPF cut-off frequency [12]

5.9 MPPT

According to [37] Maximum Power Point Tracking (MPPT) is a crucial technology that increase the performance and output of solar photovoltaic (PV) systems. Its primary goal is to consistently optimize the optimal operating point, known as the maximum power point (MPP), of solar panels. This ensures the extraction of the greatest possible amount of power from sunlight, thereby maximizing the system's efficiency and output.

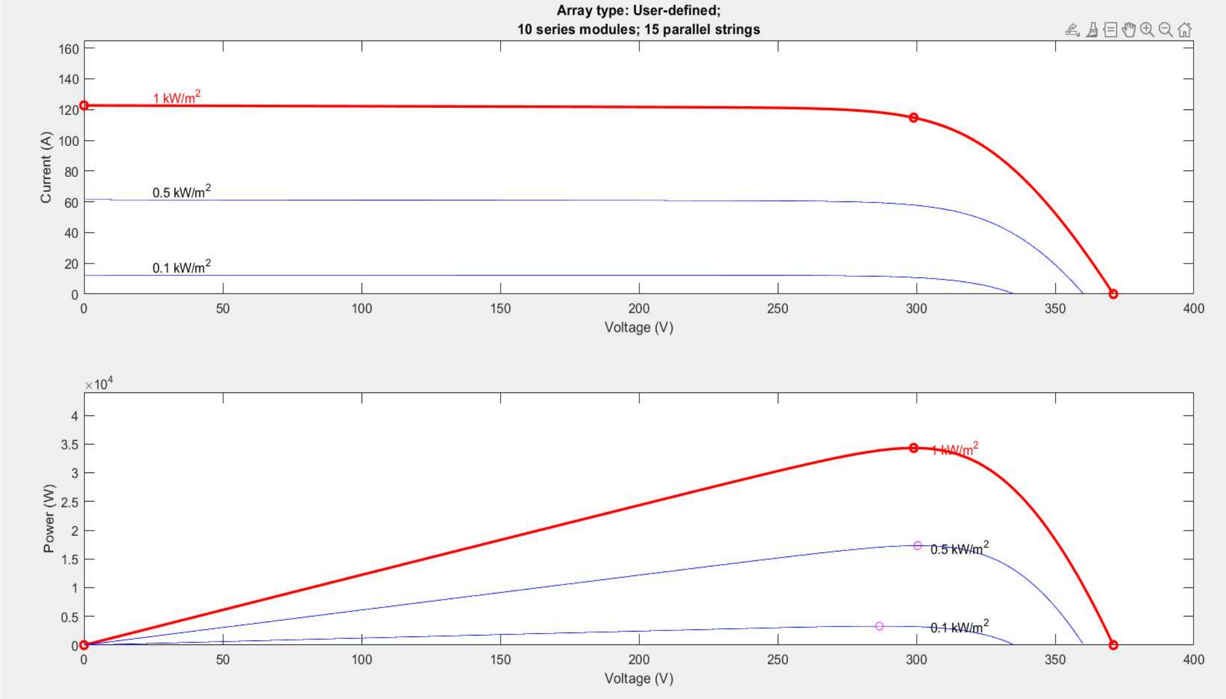

Figure 10 IV and PV curve of the PV system

5.10 Droop Control

Droop control is a method used to manage synchronous generators and inverter-based resources within electrical grids. It enables the parallel connection of multiple generation units, allowing them to share loads according to their power capacities. In this system, each generator in the grid is assigned specific droop values for frequency and voltage. These values set up the allowable deviations from their nominal value to accommodate fluctuations in power demand.

The most common type of droop control is conventional droop control. In conventional droop control, frequency and voltage vary linearly with respect to active and reactive power, respectively. For instance, assigning a 1% frequency droop to a converter means that its frequency deviates 0.01 per unit (pu) in response to a 1.0 pu change in active power. Reverse droop control is an alternative technique that can be useful in low-voltage microgrids. [38]

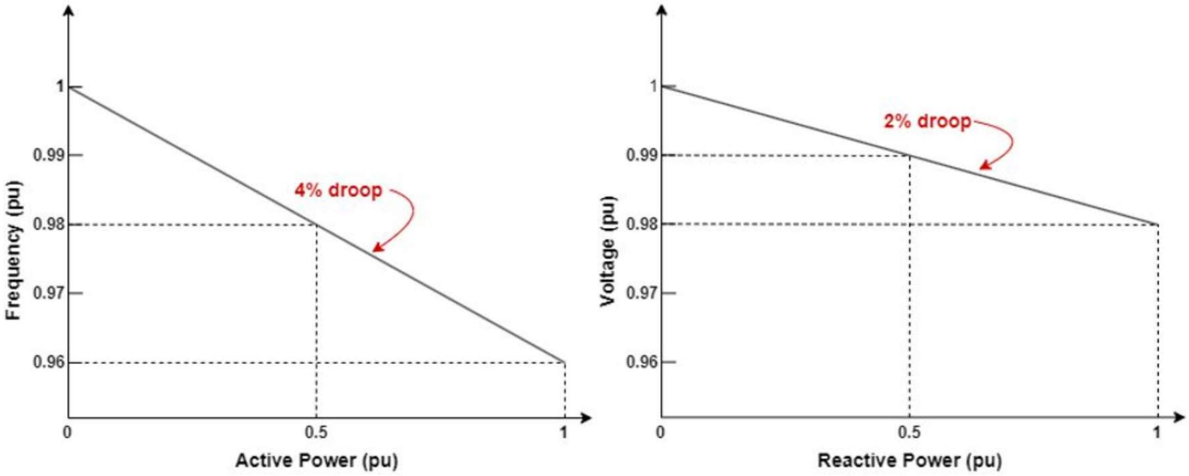

Figure 11 Frequency and voltage conventional droop curves

5.11 Phase Locked Loop

PLL is well-defined in literature [39]. A phase locked loop(PLL) is a control system that produces an output signal synchronized with an input signal's phase. PLLs are commonly employed for synchronization. In three-phase systems, the most extended method for grid synchronization is the Synchronous Reference Frame PLL (SRF-PLL). Therefore, to detect and regulate the phase, frequency, and amplitude of both grid and inverter voltages, the SRF-PLL use for as an effective synchronization technique.

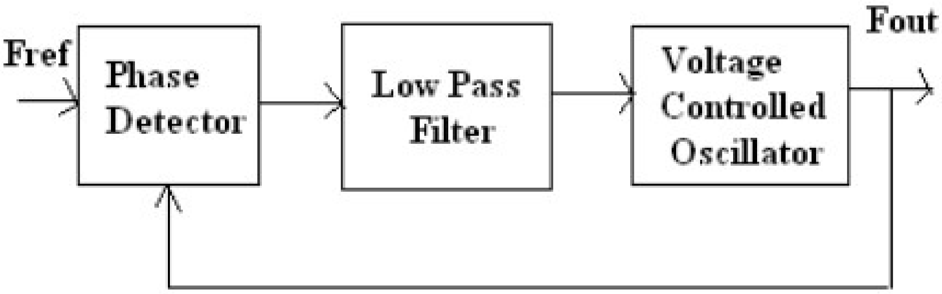

Figure 12 PLL

5.12 DFIG

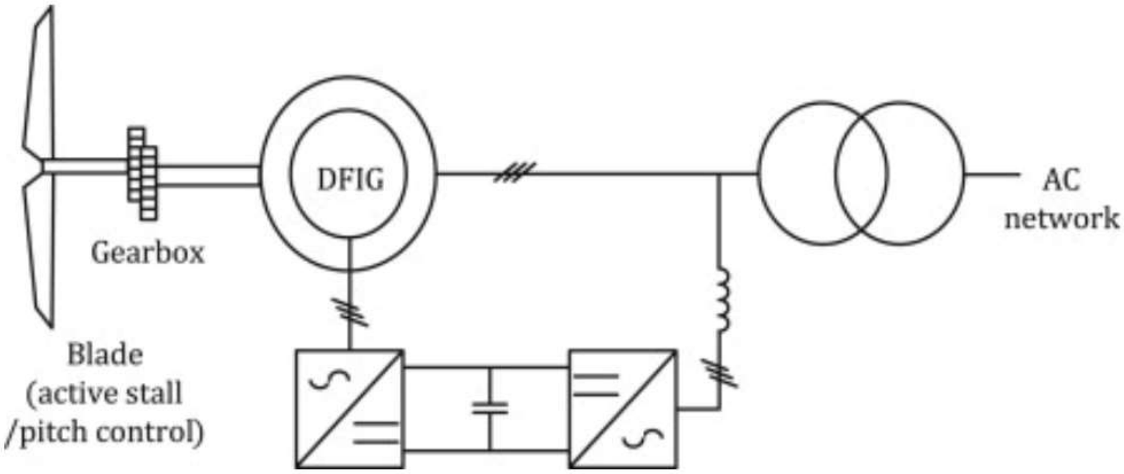

Figure 13 Doubly fed induction generator

A Doubly Fed Induction Generator (DFIG) features a wound-rotor induction generator and is linked to the AC network via a back-to-back converter, as shown in Figure 13. This setup enables the control of rotor current frequency, allowing energy exchange between the rotor and the AC network. As a result, the DFIG can operate at varying rotor speeds and manage the output of real power smoothly. The converter also has the capability to flexibly supply reactive power. The adaptable control of the converter reduces mechanical stress on the wind turbines and lowers the risk of turbine failure. The converter also supports fault ride-through capabilities for the turbines, essential for adhering to grid codes. In the event of a grid fault, the DFIG can stay connected to the grid, managing real power consumption through the rotor crowbar and the DC-link chopper to prevent DC overvoltage or rotor overspeed. The converter typically has a rating of 30% of the turbine's total rating. This lower rating helps decrease both the initial investment costs and the power losses in the power electronic converter, compared to systems equipped with a full converter [40].

5.13 Primary Frequency Control

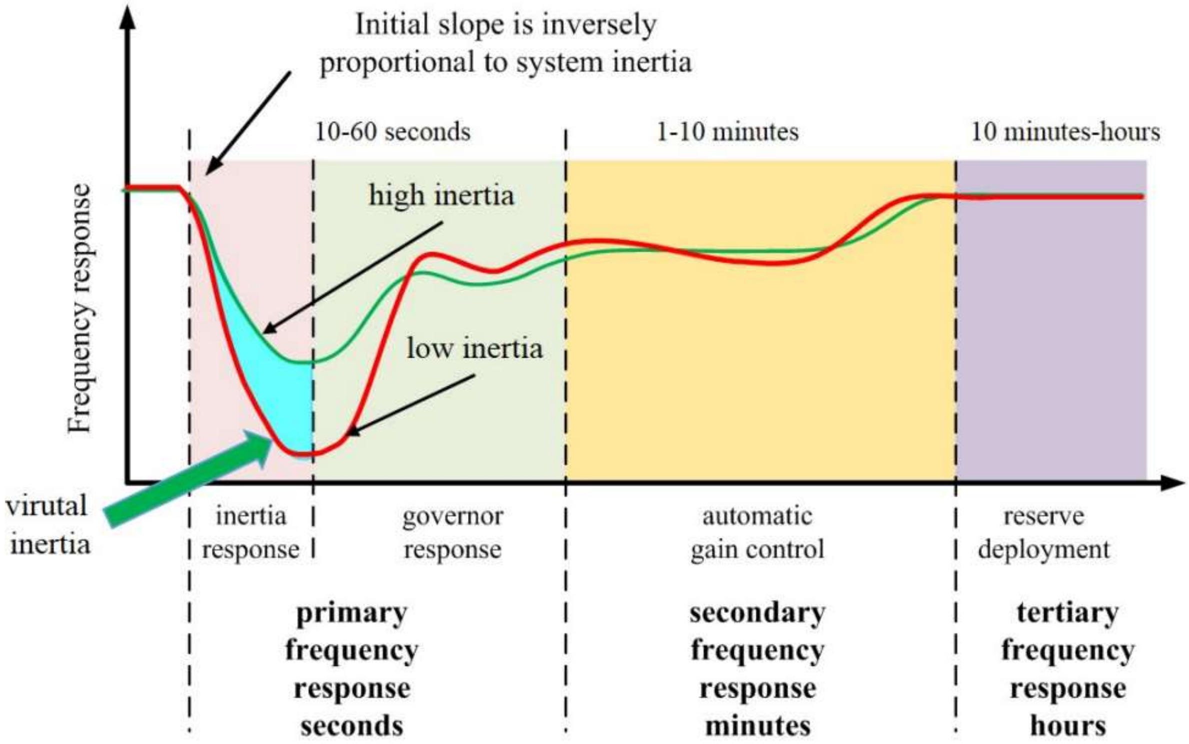

Figure 14 Frequency control system

Primary frequency response occurs within the first few seconds following a disturbance that alters the system frequency. During this critical time, governors on generators and motor loads play a crucial role. Generator's governors adjust valve openings to regulate diesel flow, ensuring a balance between load and generation. Similarly, motors connected to the system operate at lower speeds when the system frequency decreases, thereby drawing less energy from the grid.

Primary frequency response holds particular significance in islanded microgrids, where the grid operates independently from the main utility network. The rate of change of frequency (ROCOF) during this phase is inversely related to the system's inertia. Systems with higher inertia, or spinning reserve, exhibit lower ROCOF and higher minimum frequencies for the same disturbance compared to those with lower inertia [41].

The natural frequency response of a power system, driven by the kinetic energy stored in rotating masses, provides some level of stability. However, it's insufficient to handle larger disturbances. While this natural response limits frequency deviations, additional measures are required to maintain stability, especially during significant disturbances.

In power systems, three levels of control are typically employed to ensure a balance between generation and load. Primary control is the first line of defense, acting locally and automatically to adjust power generation and controllable loads in response to frequency variations. It works swiftly, within seconds, and is designed to counteract large generation changes or load shifts. While primary control can handle small frequency deviations, secondary control steps in to address larger deviations and restore nominal frequency. Speed governors, operating within the synchronization region of generation units, play a crucial role in secondary control by adjusting power output.

Demand-side resources also contribute to frequency control by connecting or disconnecting loads based on frequency thresholds. Although not always considered in primary control, these demand-side measures are significant. Distributed primary frequency control, where multiple units share the increase in power demand resulting from a frequency drop, can be advantageous for system stability. Speed governors come in various forms, including isochronous regulation, droop control, and virtual inertia. These strategies are not only applicable to traditional generators but can also be implemented in power converters for modern grid operation, ensuring stability and reliability in diverse energy environments. [42]

In microgrids with low inertia, such as PV-diesel generator setups, frequency relays may trip, leading to dynamic frequency stability issues. To address this, external inertia may be added to improve the system's dynamic frequency stability. This could involve various strategies, such as integrating energy storage systems or implementing virtual inertia to emulate the inertial response of traditional synchronous generators [43].

5.14 Secondary Frequency Control

The secondary frequency control, operating in a centralized manner, ensures that power production from generator units is adjusted to restore the system frequency to its nominal value. Unlike primary control, which focuses on limiting frequency excursions, secondary control aims to return the frequency to its original equilibrium point the nominal frequency. This approach is primarily used in large interconnected systems where a rapid response is necessary, but it's typically not essential in isolated systems. AGC combines dispatching and secondary control, operating within a timeframe of seconds to minutes. While primary control handles immediate deviations, secondary control fine-tunes power production to bring the frequency back to its target value. It's usually focused on generator units, with loads not typically participating. While some power systems may rely solely on primary and manual tertiary frequency control, secondary control is adopted in all large interconnected systems to swiftly address overloads that manual action alone may not resolve [44] [45].

5.15 Tertiary Frequency Control

The tertiary control reserve, also known as manual Frequency Restoration Reserve (mFRR) by ENTSO-E, is manually activated by the system operator as needed. It serves to relieve the secondary reserve, especially after significant generation or load power losses, or to address forecast errors. Since power imbalances can be either negative or positive, the tertiary reserve is deployed for both upward and downward regulation. If the secondary reserve is extensively utilized, it may deplete primary reserves, indicating the need for tertiary reserve activation. This reserve capacity can be provided by both spinning and non-spinning generators [46].

6 Methodology

6.1 Design And simulation of System Configuration

All figure and data from [47] and [12] except Matlab simulation model.

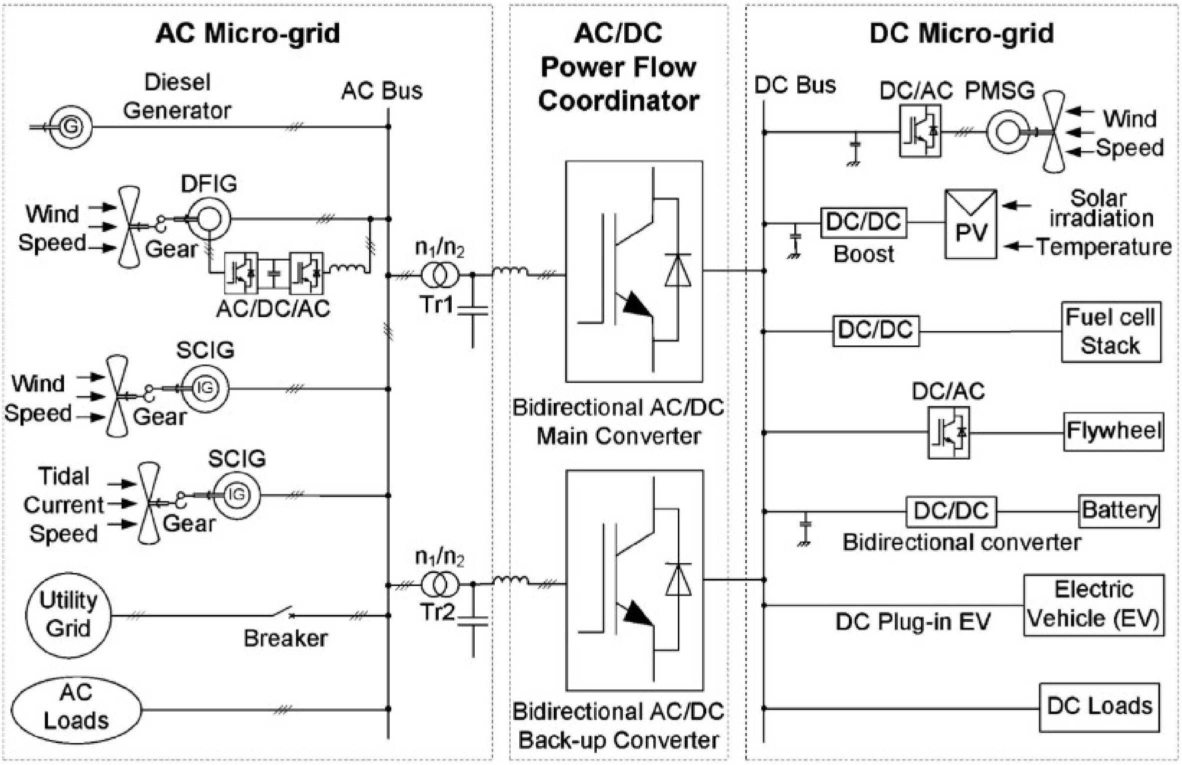

Figure 15 Hybrid ac/dc microgrid system

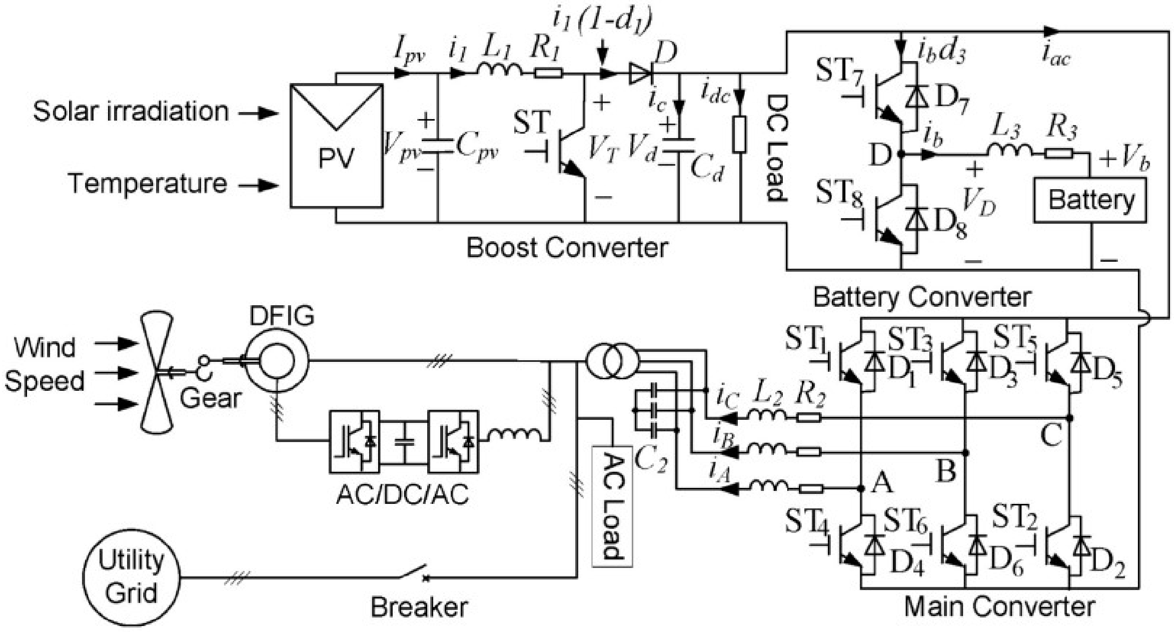

Figure 16 A compact representation of the proposed hybrid grid

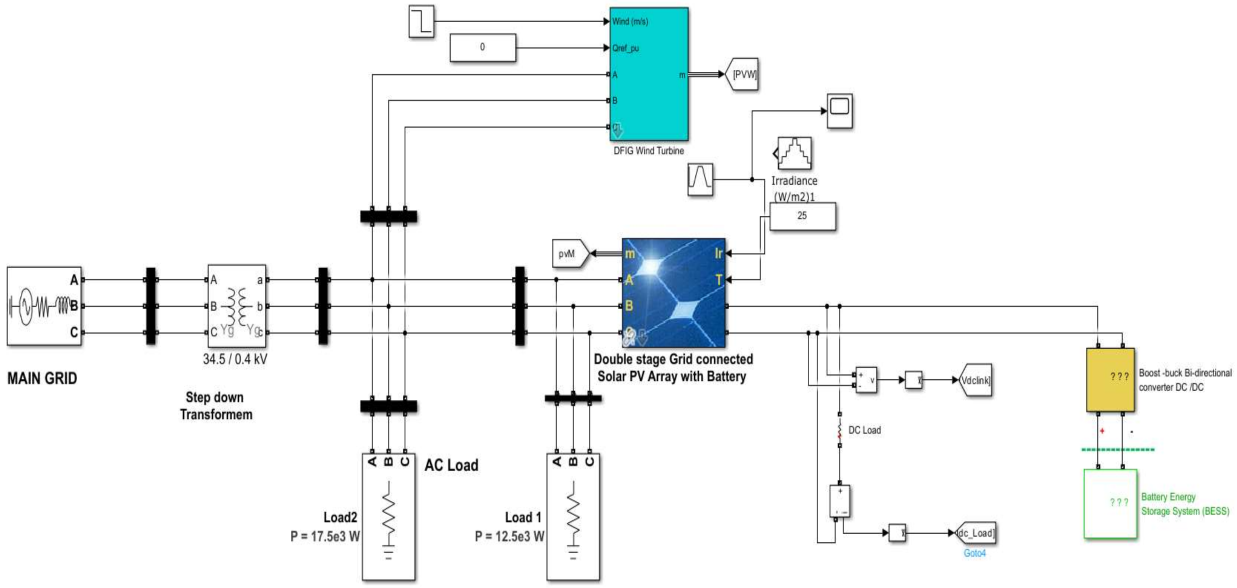

Figure 17 A hybrid ac/dc microgrid matlab simulation model

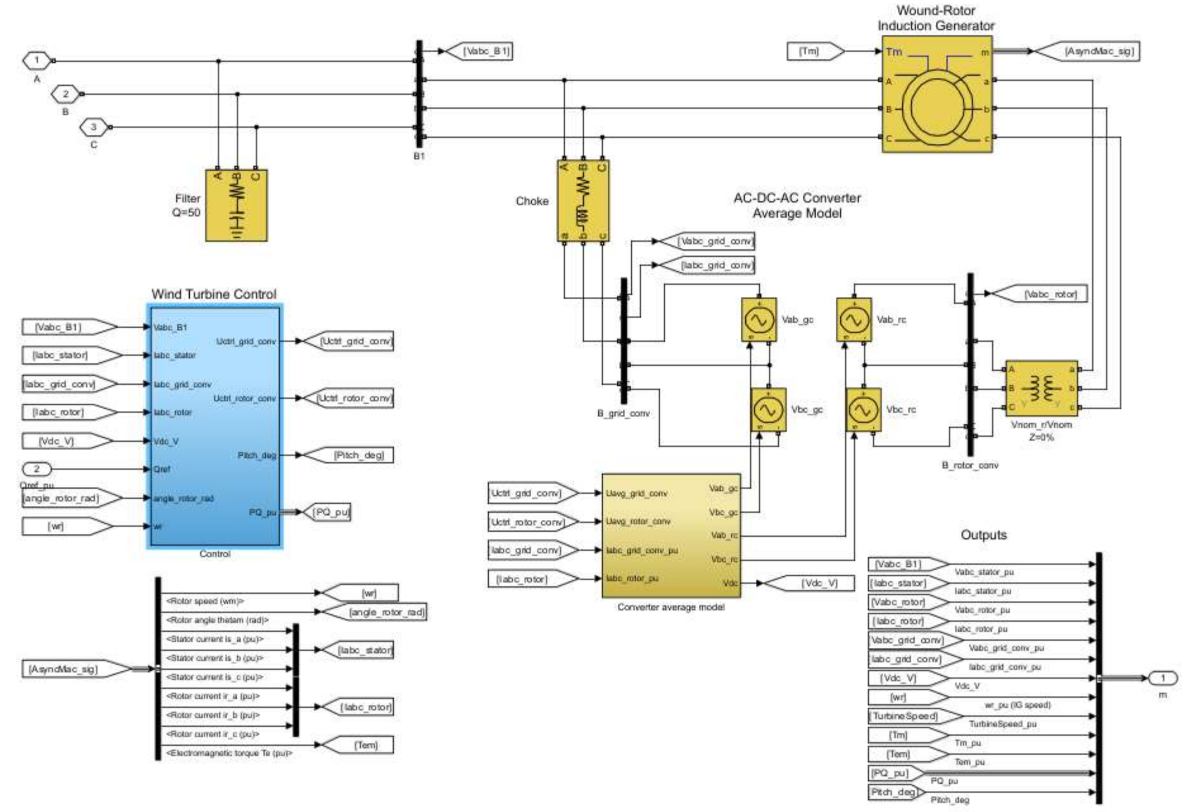

Figure 18 DFIG matlab simulation model

Tabell 1 Parameter for DFIG

Symbol	Description	Value
P_{nom}	Nominal power	50 kW
V_{nom}	Nominal voltage	400 V
R_s	Stator resistance	0.023 pu
L_s	Stator inductance	0.18 pu
R_r	Rotor resistance	0.016 pu
L_r	Rotor inductance	0.16 pu

L_m	Mutual inductance	2.9
J	Rotor inertia constant	3 s
n_p	Number of poles	6
V_{dc-nom}	Nominal DC voltage of AC/DC/AC converter	800 V
P_m	Nominal mechanical power	45 kW
f_{nom}	Nominal frequency	50 Hz
T	Transformer	800V/400V

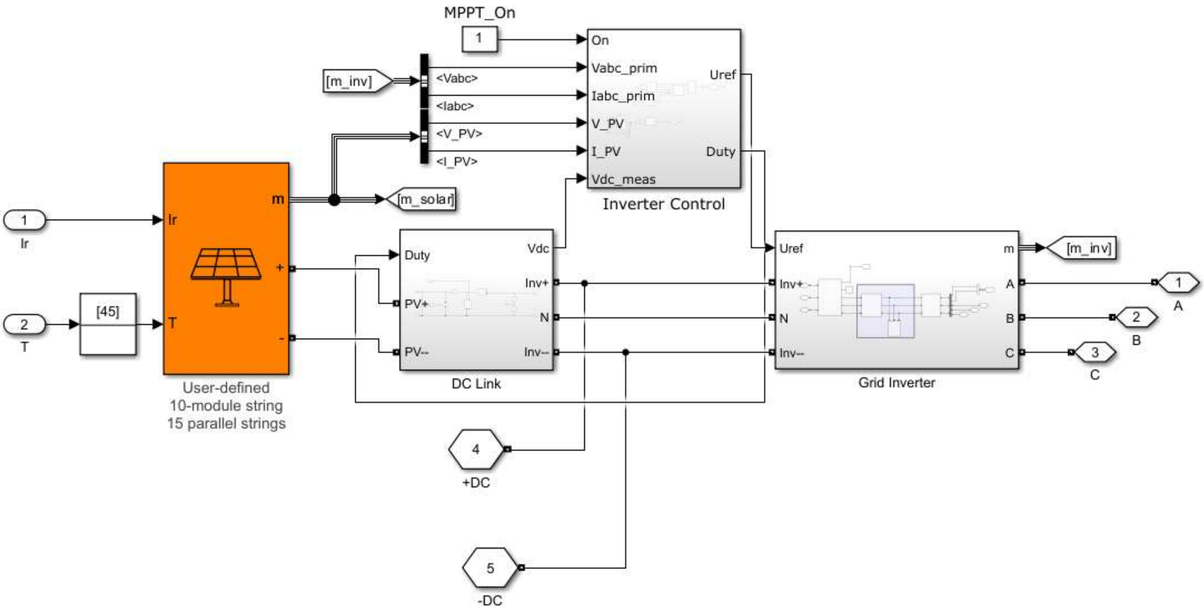

Figure 19 PV system connected with grid matlab simulation model

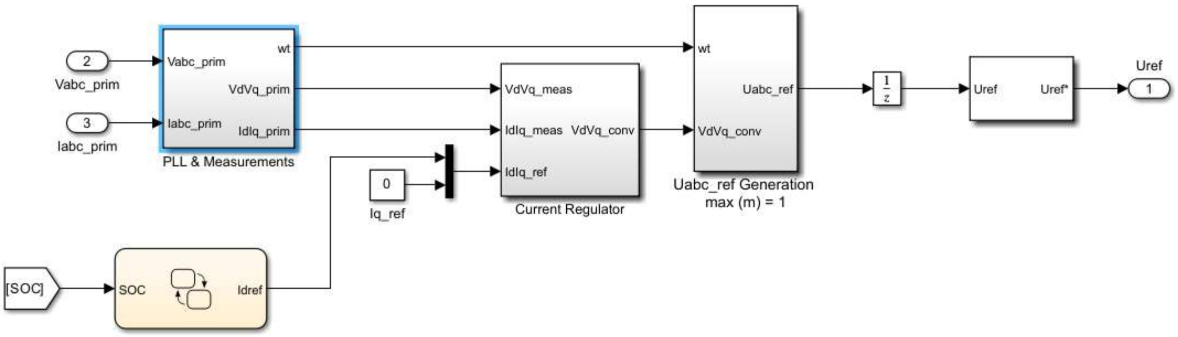

Figure 20 control system matlab simulation model

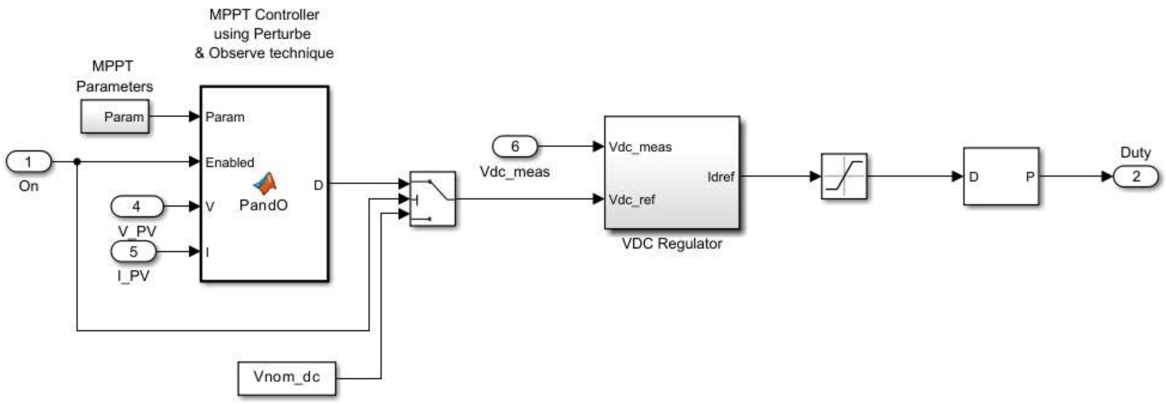

Figure 21 MPPT matlab simulation model

Tabell 2 Parameter for PV

Symbol	**Description**	**Value**
V_{oc}	Rated open circuit voltage	37.1 V
q	Electron charge	$1.602*10^{-19}$ C
A	Ideality factor	1.5
k	Botzman constant	$1.38*10^{-23}$ J/K
I_{sc}	Short-circuit current	8.18 A
k_i	SC temperature coefficient	$1.7e^{-3}$
T_r	Reference temperature	318 K
I_{rr}	Reverse saturation current at T_r	$2.0793*10^{-6}$ A
E_{gap}	Energy of the band gap for silicon	1.1eV
n_p	Number cells in parallel	15
n_s	Number of cells in series	10
S	Solar radiation level	0-1000 W/m^2

T	Surface temperature of the pv	350 K

Tabell 3 Control parameter

Parameter	**Value**	**Parameter**	**Value**
K_p	0.01	k_{pf}	0.005
K_q	0.05	k_{if}	0.2
K_{dc}	0.05	k_{pv}	0.05
K_{ac}^{ic}	100	k_{iv}	2.5
K_{dc}^{ic}	20	k_{pvdc}	0.25
w_c^{ic}	5 rad/sec	k_{ivdc}	5
ω_c^{dc}	5 rad/sec	ω_c^{ac}	100 rad/sec

Where k_{pf}, k_{if}, k_{pv}, k_{iv}, k_{pvdc} and k_{ivdc} are the proportional and integral gain constant of the frequency restoration controller, AC bus voltage restoration controller and DC bus voltage restoration controller.

The figure 15 provided illustrate the configuration of a hybrid energy system, showcasing the interconnection of various AC and DC sources and loads with their respective networks. In this setup, AC and DC links are bridged through two transformers and two four-quadrant operating three-phase converters. Additionally, the AC bus of the hybrid grid is linked to the utility grid, allowing for integration with external power sources.

Figure 16 and 17 shows the model and simulate the operation and control of this system, a compact representation is constructed using Simulink in MATLAB. Specifically, the setup includes 35 kW photovoltaic (PV) arrays connected to the DC bus via a DC/DC boost converter to mimic DC sources. A capacitor is employed to mitigate high-frequency ripples in the PV output voltage. Furthermore, a 45 kW wind turbine generator (WTG) with a doubly fed induction generator (DFIG) is linked to an AC bus to represent AC sources.

For energy storage, a 400 Ah battery is connected to the DC bus through a bidirectional DC/DC converter. Variable DC loads ranging from 10 kW to 35 kW and AC loads ranging from 10 kW to 40 kW are connected to the DC and AC buses, respectively. The rated voltages for the DC and AC buses are maintained at 400 V and 400 V rms, respectively. Three-phase bidirectional DC/AC main converter, equipped with an R-L-C filter, serves to bridge the DC bus with the AC bus through an isolation transformer. Frequency control, also known as frequency response, is crucial for maintaining the stability of a power system. When there's a sudden loss of generation or an increase in load, the frequency of the system can drop. To address this, Energy Storage Systems (ESS) can step in to provide the needed power and stabilize the frequency. ESS can play roles in both primary and secondary frequency control. Primary frequency control acts quickly, lasting only a few seconds, while secondary frequency control provides support over a few minutes. [47]

6.2 Management And Control of Power System

The hybrid grid operates in two modes: grid-tied mode and autonomous mode, each with specific operational characteristics and control objectives.

In grid-tied mode, the main converter assumes a critical role in maintaining stable DC bus voltage and fulfilling reactive power requirements while facilitating power exchange between the AC and DC buses. The boost converter and wind turbine generator (WTG) are optimized to deliver maximum power output. When the DC sources generate surplus power compared to the DC loads, the main converter functions as an inverter, channelling excess power from the DC to AC side. Conversely, when the total power generation falls short of the total DC load, the converter transfers power from the AC to DC side. If the overall power generation exceeds the hybrid grid's demand, surplus power is exported to the utility grid, whereas the hybrid grid imports power when demand surpasses generation. In this mode, the battery converter's role is minimized as power balance is primarily managed by the utility grid.

In autonomous mode, the battery assumes a pivotal role in maintaining power balance, frequency control and voltage stability within the system. Control objectives for all converters are orchestrated by the energy management system, with particular emphasis on stabilizing the DC bus voltage. The main converter ensures a stable and high-quality AC bus voltage. Both the PV arrays and WTG can operate in maximum power point tracking (MPPT) or off-MPPT mode based on system requirements. Variations in wind speed and solar irradiation are simulated to assess the performance of the MPPT control algorithm and adapt system operation accordingly. This mode highlights the criticality of energy storage and advanced control strategies for ensuring reliable and resilient operation in isolated or off-grid scenarios. [47]

6.3 Coordination Control Of The Converters at Isolated Mode

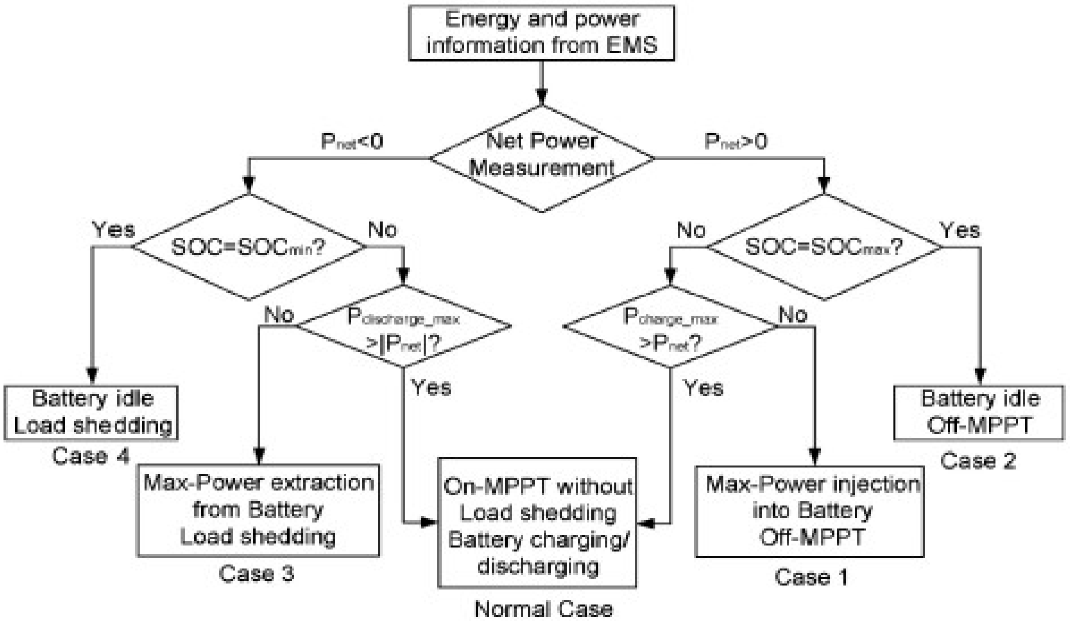

Figure 22 Control diagram og hybrid microgrid

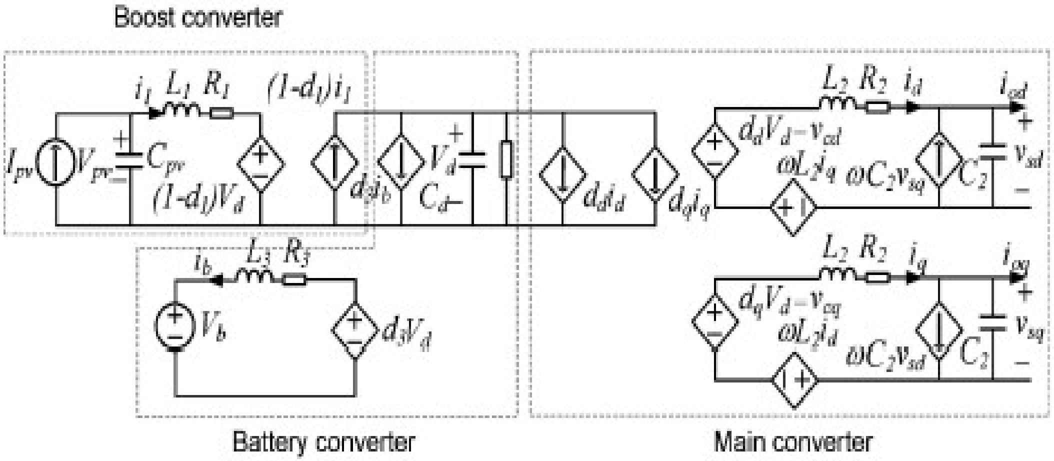

Figure 23 Time average equivalent circuit model for the three converter

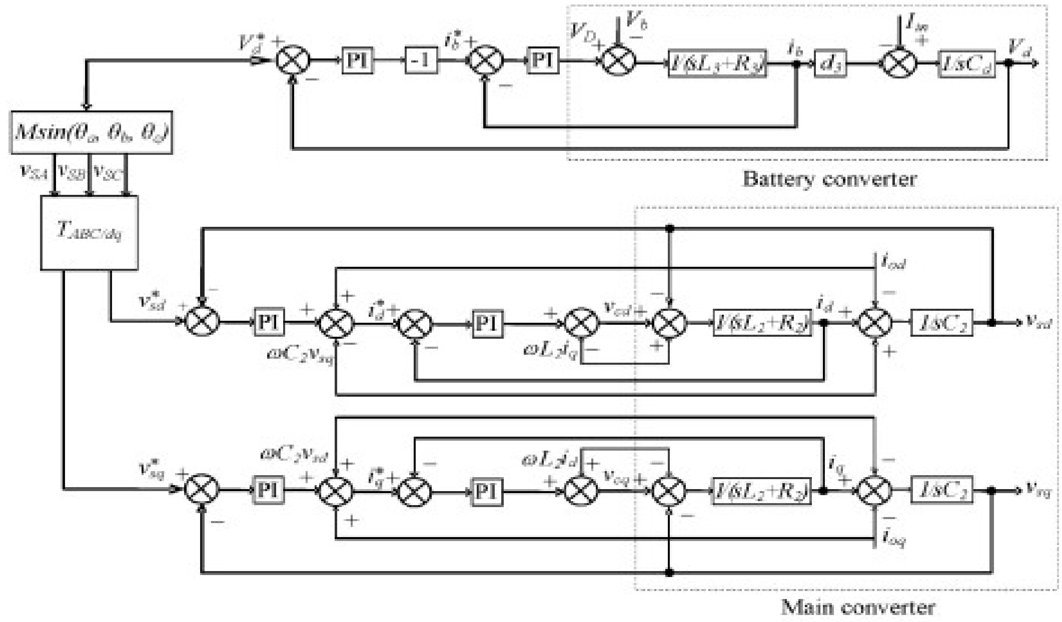

Figure 24 Block diagram of the battery and main converters for the normal case

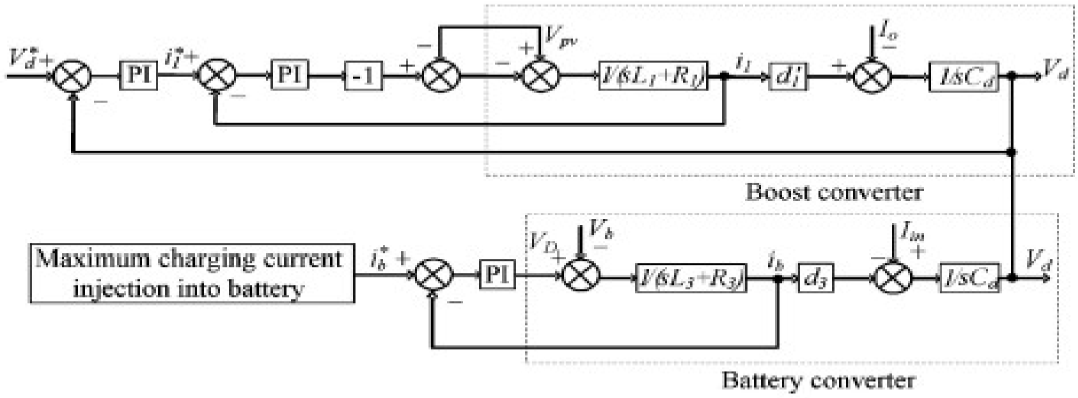

Figure 25 Block diagram of the booster and battery converter for case 1

When the hybrid grid transitions into islanding mode, the operational strategies of the boost converter, the back-to-back AC/DC/AC converter of the doubly fed induction generator (DFIG), the main converter, and the battery converter are adapted to ensure stable and efficient operation within the isolated system. The boost converter and the DFIG's AC/DC/AC converter may operate either on-MPPT or off-MPPT, depending on the prevailing system power balance and energy constraints. These converters dynamically adjust their operating modes to optimize power generation and utilization within the islanded grid. The main converter serves as a voltage source, providing stable voltage and frequency for the AC grid. It operates either as an inverter or a converter to facilitate smooth power exchange between the AC and DC links, ensuring efficient energy transfer within the system. Similarly, the battery converter operates in either charging or discharging mode, responding to the power balance within the system. It dynamically adjusts its operation to maintain stability and meet the energy demands of the islanded grid. The DC-link voltage is regulated either by the battery or the boost converter, depending on the system's operating conditions and requirements. Under various load and supply conditions, the powers exchanged within the system must be balanced to maintain operational stability and reliability. The coordinated actions of the converters and energy storage devices ensure that power flows are managed effectively, mitigating potential disruptions and enhancing the resilience of the islanded grid. As follow:

$$P_v + P_w = P_{acL} + P_{dcl} + P_{loss} + P_b \qquad (4)$$

Where P_{loss} is the total grid loss

A two-level coordination control strategy is employed to ensure the stable operation of the system during islanding mode. At the system level, the operation modes of individual converters are determined by the Energy Management System (EMS) based on factors such as the system's net power, energy constraints, and the charging/discharging rate of the battery. The control logic diagram for the system is depicted in Figure 22. The net power (P_{net}) is calculated as the total maximum power generation minus the total load and minus P_{loss}. The energy constraints for the battery are derived from the state of charge (SOC) limits using $SOC_{min} < SOC < SOC_{max}$. Although SOC cannot be directly measured, it can be estimated using various methods. Additionally, the charging and discharging rates are constrained by $P_b \leq P_{bmax}$. At the local level, individual converters operate based on mode commands received from the EMS. Depending on the specific case, either the PV system, the WTG, or both may operate in off-MPPT mode for Case 1 and Case 2, while they operate in on-MPPT mode for other cases. The battery converter may operate in idle, charging, or discharging mode, depending on the system’s requirements. The main converter switches to inverter mode if $P_w - P_{acL}$ is negative, or in converter mode if $P_w - P_{acL}$ is positive. Load shedding is implemented if power supply falls short of demand and the battery’s SOC is at its minimum.

The time-average equivalent circuit model of the booster, main converter, and battery converter for isolated operation is shown in Figure 23. The current and voltage equations governing the behaviour of the battery converter and DC link are provided as follows:

$$V_D - V_b = L_3 \cdot \frac{di_b}{dt} + R_3 i_b \qquad (5)$$

$$V_d = V_d \cdot d_3 \qquad (6)$$

$$i_1(1-d_3) - i_{ac} - i_{dc} - i_b \cdot d_3 = i_c = C_d \cdot \frac{dV_d}{dt} \qquad (7)$$

Where d_3 and $(1-d_3)$ are the duty ratio of the switches ST_7 and ST_8.

The ac side current equations of the main converter in d-q coordinate as follows.

$$C_2 \frac{d}{dt}\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix}\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} - \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} \qquad (8)$$

Where i_{od} and i_{oq} are d-q current at the converter side of the transformer.

Multi-loop voltage control for a DC/AC inverter, aims to ensure high-quality AC voltage with robust dynamic response across different load conditions. This control scheme can be adapted for the main converter in standalone mode with minor adjustments. The coordinated control block diagram for normal operation is shown in Figure 24. To maintain a stable DC-link voltage, a dual-loop control scheme is implemented for the battery converter. The injection current $I_{in} = i_1(1-d_1) - i_{ac} - i_{dc}$ is regulated, where the output of the outer voltage loop is scaled by a factor before being used as the inner loop current reference. The current is considered positive when flowing into the battery, and the preset DC-link voltage is maintained constant at 400 V. In response to deviations in the DC-link voltage caused by sudden load changes or variations in solar irradiation, the control system adjusts the battery converter's operation mode accordingly. A positive voltage error, multiplied by a factor, drives the inner current loop to transition the battery from charging to discharging mode, or vice versa, to restore the DC-link voltage to its preset value. Meanwhile, the main converter ensures a stable AC bus voltage for the doubly fed induction generator (DFIG) converter, as illustrated at the bottom of Figure 24.

As the system transitions between different operating scenarios, the control objectives for the converters evolve accordingly. For instance, in cases where the boost converter is tasked with maintaining a stable DC-link voltage instead of MPPT (as in cases 1 and 2), and the battery converter may be controlled to maximize power absorption (case 1) or switched off entirely (case 2). The coordinated control block diagram for these converters in Case 1 is presented in

Figure 25, where the boost converter stabilizes the DC-link voltage, while the main converter ensures a stable AC bus voltage.

In addition to voltage control and power management, implementing anti-islanding techniques is crucial for ensuring the reliable operation of distributed generation systems. Various detection and control schemes have been developed for conventional and power-converter-based distributed generators and microgrids, which can be adapted and integrated into the proposed hybrid grid to facilitate seamless transitions between grid-tied and isolated modes. [48]

7 Simulation Result

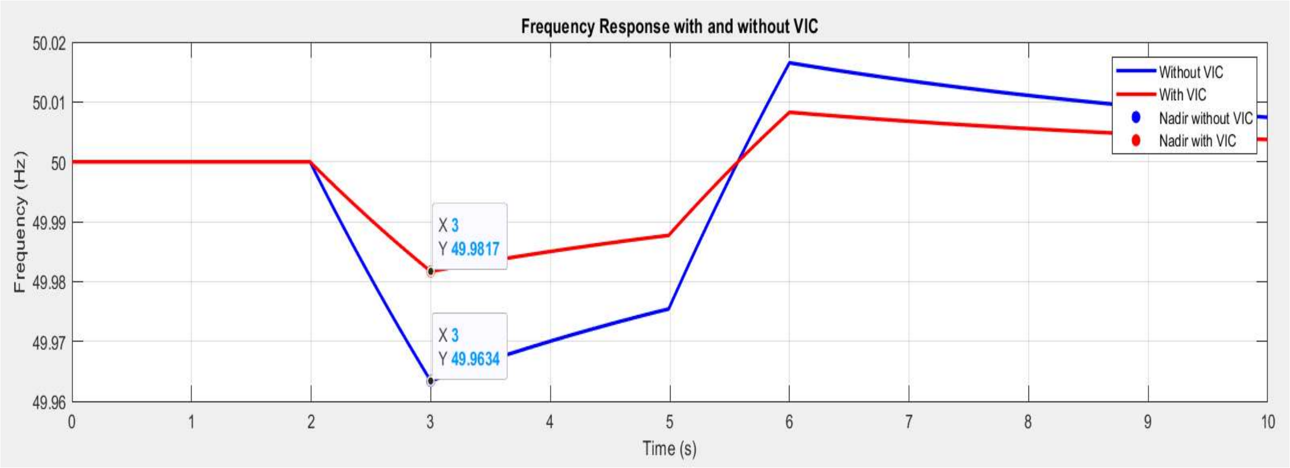

Figure 26 Frequency change with 20% load change

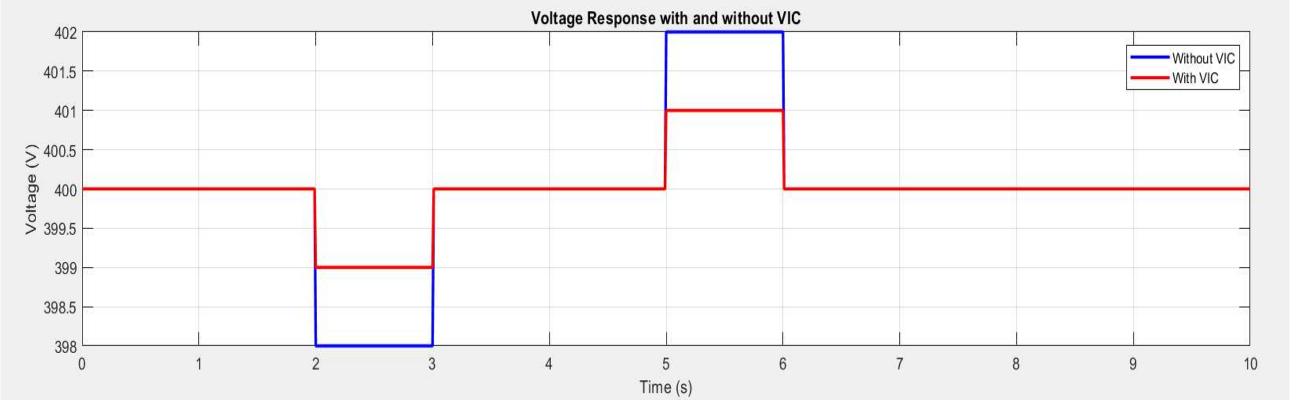

Figure 27 Voltage change with 20% load change

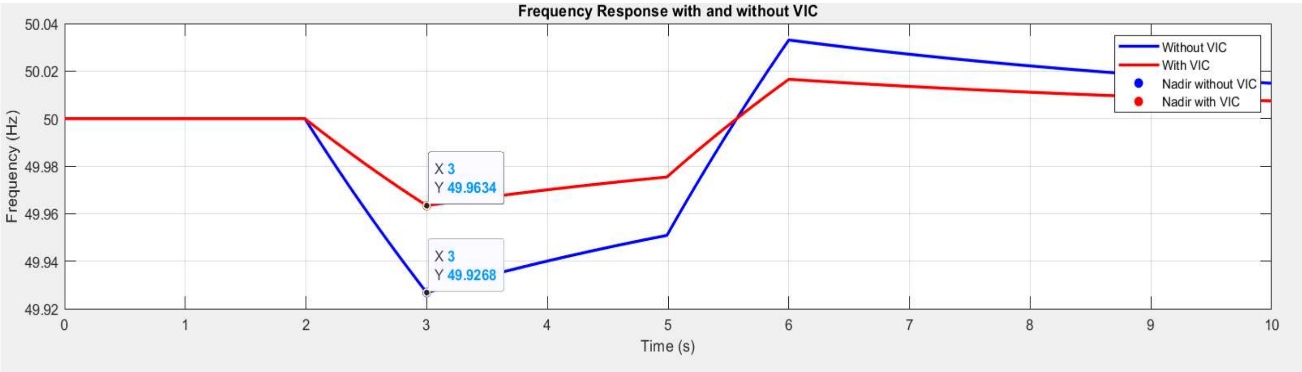

Figure 28 Frequency change with 40% load change

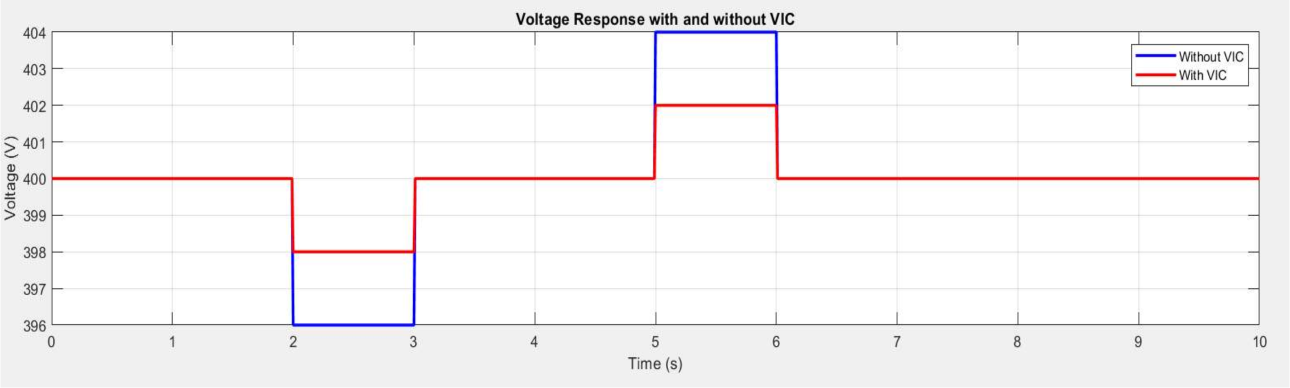

Figure 29 Voltage change with 40% load change

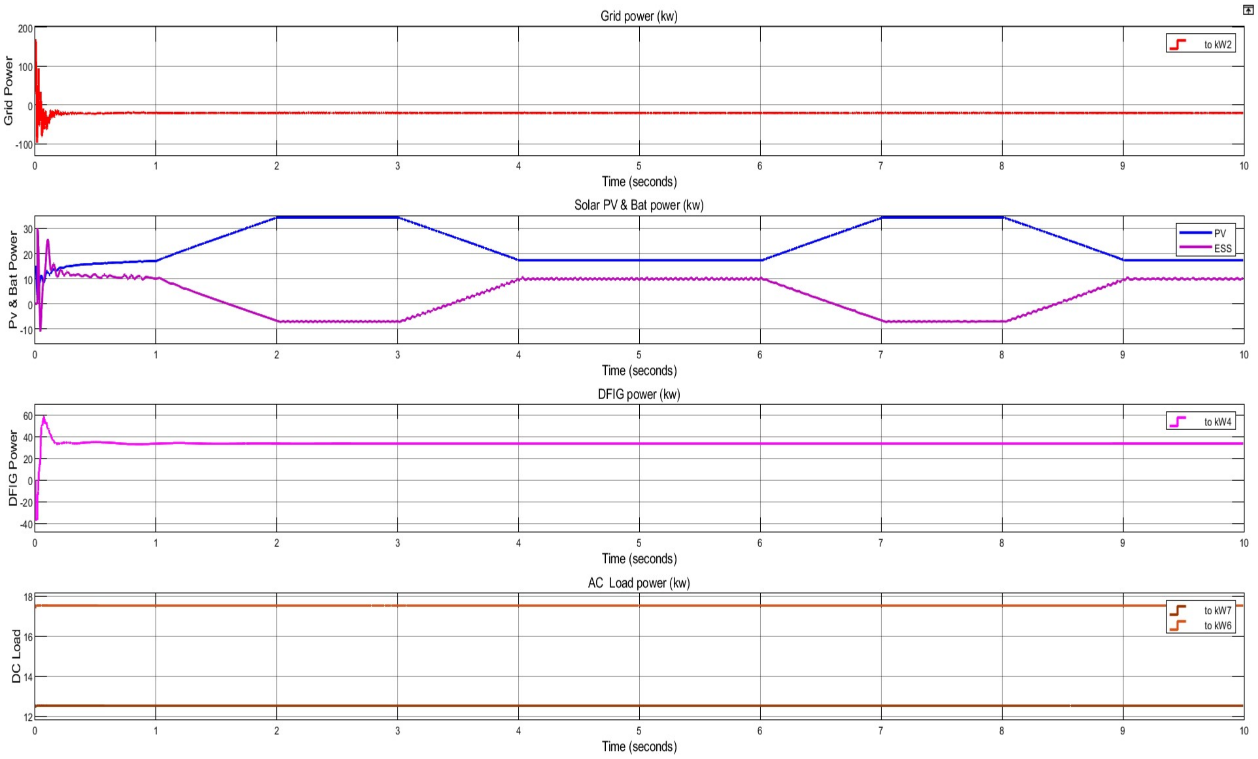

Figure 30 Output power of the system

The two case studies were simulated disturbances of step-up and step-down of 20% load on the AC-subgrid, and step-up and step-down of 40% load on AC subgrid.

Figure 26 and figure 28 shown the ROCOF and frequency nadir and figure 27 and figure 29 shown voltage difference between with VIC and without VIC. In this case i used ESS for VIC. Through the step-up tests the load was initially set to 10 kW, the bus voltage at 400 V and frequency at 50 Hz. For the Step-down tests the load was initially set to 12 kW it means changes the load 20%. Then again the step-up tests the load was initially set to 10 kW, the bus voltage at 400 V and frequency at 50 Hz. For the Step-down tests the load was initially set to 14 kW it means changes the load 40% .

Figure. 26 and 28 shows how the virtual inertia control (VIC), after the load disturbance, reduces the frequency Nadir and improves steady state offset of the bus voltage, compared to operating without the VIC.

8 Conclusion

This study explores the use of virtual inertia to improve the performance of a Hybrid AC/DC Microgrid, addressing challenges arising from reduced system inertia due to increased renewable energy integration. Virtual inertia, through active power adjustments, proves effective in slowing the Rate of Change of Frequency (ROCOF) and preventing critical frequency levels during disturbances. The research emphasizes the importance of virtual inertia controllers in stabilizing microgrids lacking physical inertia.

In this project discuses Matlab simulation for compare ROCOF and frequency nadir with VIC and without VIC, power system arrangements, bidirectional interlinking converter, highlighting complexities introduced by renewable energy integration. Integrated control strategies for DC and AC subgrids, including ESS and droop control, are proposed to ensure stability and power sharing. The simulation results demonstrate the effectiveness of virtual inertia in reducing frequency nadir and improving DC bus voltage stability during disturbances.

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