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Simulation, Analysis Of DC Microgrid Using Bi-Directional DC-DC Converter

[1]Monish K V, [2]Sachin M, [3]Yashas N, [4]Kruthi Jayaram
[1]Student, [2]Student, [3]Student, [4]Assistant Professor
[1] Dept. of EEE,
[1] BNM Institute of Technology, Bengaluru, INDIA

Abstract: Microgrids are small-scale energy systems that may function both separately and in tandem with the larger power grid. They are made up of dispersed sources of energy, such as photovoltaics, wind, battery and traditional generators, along with advanced control systems. Although microgrids been accessible for many years, the military and college campuses were the main users until recently. Thus, while still relatively modest, the overall number of microgrids is increasing. By 2028, Guide House (formerly Navigant) predicts that the market will be close to $39.4 billion. The DC microgrid is designed to manage energy generation, storage, and distribution efficiently. A bidirectional converter is employed to facilitate seamless energy exchange between the grid and solutions for energy storage, guaranteeing the best energy utilization and storage. The simulation phase involves analyzing the microgrid's performance under varying load and generation conditions using MATLAB/Simulink.

Index Terms - DC Microgrid, Boost Converter Design, Bi-directional Converter Integration, MPPT Implementation, Dynamic Load Management, Simulation and Validation.

I. Introduction

A microgrid is a set of distributed energy resources and associated loads that works as a single, controllable unit in relation to the grid. It operates in island mode or disconnects and connects. Microgrids could improve resilience to grid disruptions and consumer dependability[1], [2].

As the world's energy demands grow, so does the urgency to find sustainable ways to meet these needs. Conventional fossil fuel-based power systems are not only limited, but they also negatively affect the environment. This has accelerated the changeover to clean, numerous, and sustainable renewable sources of energy like wind and solar. Among the innovative approaches to integrating these sources into modern power systems, DC microgrids stand out as a game-changing solution. These advancements have been widely studied in literature, highlighting their potential to revolutionize renewable energy systems [4], [6], [8].

This paper, titled "Simulation and Hardware Analysis of DC Microgrid Using Bi-directional Converter," focuses on creating a practical, efficient, and reliable DC microgrid. It includes designing, simulating, and testing a mechanism that not only produces power from renewables but also stores and distributes it intelligently. The goal of this paper is to address the main obstacles in renewable energy variability and effective energy management while making renewable power more accessible and consistent. This aligns with previous works emphasizing the role of energy management systems and advanced control strategies [6], [8], [13].

Among the most major barriers to sustainable energy is its inconsistency. Solar panels depend on sunlight, and wind turbines need wind, both of which can fluctuate throughout the day or season. This makes it hard to ensure a steady supply of power. On top of that, traditional AC Grids of electricity are not built to manage such irregularities well. They require energy to be converted multiple times—from DC (produced by solar or wind) to AC for distribution, and sometimes back to DC for modern devices—causing significant energy losses [4], [10].

DC microgrids solve these issues by simplifying the process. They directly use the DC power generated by renewable sources without needing extra conversion steps. In addition to increasing efficiency, this also reduces the difficulty of system. Additionally, DC microgrids can function separately from the grid, which is perfect for remote areas and critical facilities like hospitals, where a stable and dependable power source is crucial [7], [11].

DC Microgrid interconnects renewable energy sources, energy storage system and loads for efficient power flow management. For a efficient flow of power bidirectional DC-DC converters are used. Literature review critically examines the previous and current research on the analysis of simulation of DC microgrid.

Early works on DC microgrid focused on architecture of the system and control structures. The architecture deals with decentralized power generation, storage integration, types of power converters. In recent works, considerable increase in converter efficiency, control techniques are improved.

Despite significant advancements, gaps remain in real-time hardware validation of bi-directional converters in DC microgrids. Most simulation studies (e.g., Gao et al., 2022) focus on idealized conditions without considering practical constraints such as converter losses, communication delays, and cyber-security concerns. The novelty of this work lies in bridging this gap by implementing a real-time hardware-in-the-loop (HIL) simulation and experimental validation of a bi-directional converter-based DC microgrid.

This paper goal is to develop and execute a functional DC microgrid that integrates sustainable sources of energy with advanced energy management systems. To achieve this, the paper focuses on several key objectives:

- Boost Converter Design: The system includes a boost converter that increases the voltage generated by solar panels and wind turbines to a level suitable for distribution within the microgrid. This ensures a consistent and stable power supply.
- Bi-directional Converter Integration: A bi-directional converter manages energy storage by efficiently charging batteries when there's surplus power and discharging them when renewable generation is low.
- MPPT Implementation: To ensure that renewable sources are utilized to their fullest potential, the paper uses a Tracking Maximum Power Point (MPPT) algorithm. This algorithm adjusts the system's settings in real time to extract the maximum possible energy under varying sunlight or wind conditions.
- Dynamic Load Management: The system prioritizes renewable energy for powering connected devices. If there's insufficient power generation, it seamlessly switches to using stored energy from the batteries, ensuring uninterrupted operation.
- Simulation and Validation: Advanced software simulations test the microgrid's performance in different scenarios to confirm its stability and efficiency before it is built.

DC microgrids have a number of benefits over traditional AC systems, making them a practical choice for renewable energy applications. First, they minimize energy losses by eliminating unnecessary conversion stages. Since solar panels and batteries naturally generate and store energy in DC, these systems work more efficiently without converting it to AC and back.

Moreover, they are better suited for modern applications. Many devices, like LED lights, computers, and electric vehicles, already run on DC power. By using a DC microgrid, these devices can be powered directly, further reducing losses. Moreover, DC systems avoid common issues in AC grids, such as frequency synchronization and reactive power management, making them simpler and more reliable.

DC microgrids also bring stability to regions with unstable power supplies or no access to a central grid. They are capable of functioning on their own in isolated regions, providing power to rural communities, remote facilities, or even urban areas during grid outages. Their efficiency, flexibility, and ease of function, which makes them perfect for meeting diverse energy needs in a sustainable way.

II. LITERATURE SURVEY

The increasing reliance on the use of renewable energy has encouraged interest in innovative solutions for energy generation, storage, and distribution. Among these, DC microgrids have emerged as a transformative approach to addressing the challenges of integrating renewable energy systems. This literature survey examines the evolution of DC microgrid technology, focusing on advancements in system design, energy conversion techniques, control mechanisms, and real-world applications.

Design of DC Microgrid (2021)

This study [1], by Shah et al. focused on improving the integration of distributed photovoltaic (PV) units within DC microgrids. The research proposed a design to supply power through regular distribution lines, even during commercial grid blackouts. By integrating DC buses with commercial grids and accumulators, the study

reduced energy dissipation and facility costs caused by AC/DC conversions. The paper primarily aimed at ensuring uninterrupted power supply to loads without reliance on exclusive emergency lines.
Challenges in DC Microgrid Planning and Implementation (2023)
In this paper [2], Haridev et al. provided a thorough analysis of the technical and operational challenges associated with DC microgrids. Their analysis included insights into microgrid architectures, power quality concerns, communication issues, and economic considerations. The study also compared various global DC microgrid paper and discussed future trends, including the optimization of economic operation and advancements in protection schemes for sustainable energy systems.
Modeling and Simulation of Battery Control Systems (2022)
In another study [3], Alkhafaji and Uzun explored high-efficiency battery control systems by modeling and simulating a three-phase rectifier with DC/DC converters. Their research incorporated Pulse-Width Modulation (PWM) for efficient control and Proportional-Integral (PI) methods for bidirectional converter optimization. The system's performance was validated using MATLAB/Simulink simulations, which emphasized efficient energy storage and management for DC microgrids.
Constant Current and Constant Voltage (CC-CV) have been discussed and it has been implemented for an efficient way of charging the Battery. [17] asim and Hawas's work stands out by focusing on an isolated DC microgrid with a specific emphasis on the combined use of batteries and supercapacitors. Their comprehensive simulation under various conditions provides valuable insights into the benefits of HESS in enhancing microgrid stability. However, the study could be further strengthened by incorporating real-world experimental validations and exploring the economic implications of HESS integration. In conclusion, this paper contributes significantly to the understanding of HESS in DC microgrids, aligning with and extending recent research in the field.
Iqbal and Islam's work is notable for its early integration of bidirectional DC-DC converters in PV systems with battery storage, providing a foundational simulation framework. However, the study is primarily simulation-based and does not include experimental validation, which is crucial for assessing real-world applicability. Additionally, the system's performance under dynamic conditions, such as sudden load changes or rapid irradiance fluctuations, is not extensively analyzed. In conclusion, this paper contributes to the understanding of PV-battery integration using bidirectional converters, serving as a basis for future research that incorporates experimental validation and explores advanced control strategies for enhanced system performance.
[19] The MPC method minimizes current strains, extends battery life and enhances overall system performance in response to a step change in PV power and load demand as well as providing quicker DC grid voltage control. [20] In the case of the boost mode of operation, the P&O MPPT regulated the power of the converter at 2.2 kW regardless of the disturbances applied to the system.

III. PROBLEM STATEMENT AND OBJECTIVES

Including sources of sustainable energy such as wind and solar into modern systems for energy are crucial for sustainable development. However, the intermittent and variable nature of these resources challenges the consistency and dependability of power supply. Solar energy depends on sunlight, while wind energy fluctuates with wind speeds, making consistent power output difficult, especially in critical or remote applications [6], [12].
Traditional AC grids further complicate renewable energy integration due to conversion inefficiencies, whereas DC microgrids offer a more efficient alternative by directly connecting renewable DC sources, energy storage, and loads, minimizing conversion losses [4], [10]. Despite these advantages, challenges like managing power electronics and ensuring efficient energy transfer remain. Robust energy management systems, including precise control of power converters and effective utilization of energy storage systems, are critical to address issues like voltage instability and battery overcharging or deep discharge [8], [11].
Advanced algorithms like Maximum Power Point Tracking (MPPT), such as the Perturb and Observe (P&O) method, improve energy extraction under varying conditions. However, integrating MPPT with bi-directional converters for comprehensive energy management in DC microgrids remains a significant challenge [4], [5].
This paper aims to design, simulate, and implement an efficient DC microgrid with advanced energy management. Specific objectives include:

- Boost Converter Design: Develop a boost converter to stabilize variable renewable voltage outputs [4], [6].
- Bi-Directional Converter Integration: Manage battery storage through buck-boost operation for optimal charging and discharging [5], [8].
- MPPT Algorithm Development: Implement the P&O MPPT algorithm to maximize renewable energy extraction [4], [10].
- Dynamic Load Management: Prioritize renewable energy usage while ensuring seamless transition to battery storage during low generation periods [6], [13].

- System Simulation and Validation: Analyze microgrid performance under diverse conditions using MATLAB/Simulink [6], [9].

This approach addresses the challenges of renewable energy integration, ensuring efficiency, stability, and reliability in DC microgrids.

IV. BLOCK DIAGRAM AND DESCRIPTION

The DC microgrid system's block diagram in fig.1. represents the fundamental components and their interactions, incorporating renewable energy sources, power conversion units, loads and energy storage systems. Each block represents a critical subsystem that ensures the stable and efficient operation of the microgrid.

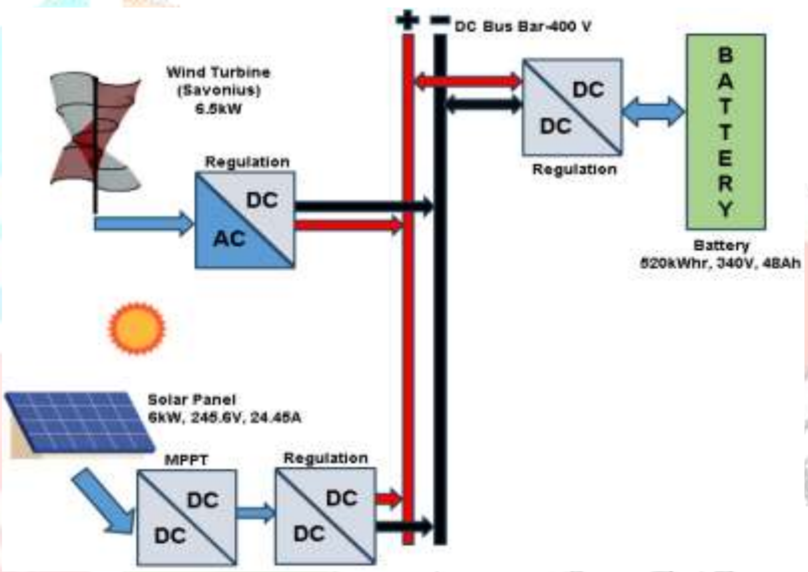

Fig. 1. Block Diagram representation of the work

1. Sources of Renewable Energy
The Microgrids incorporate wind turbines and photovoltaic (PV) panels. These components generate direct current (DC) power, which acts as the primary input for the microgrid.
Solar PV Panels: These capture sunlight and convert it into DC electricity. The output changes according to sun radiation and temperature.
Wind Turbines: It converts wind power into electrical energy. The system includes a rectifier to ensure the turbine's output is compatible with the DC microgrid.
Output: Variable DC voltage that requires further processing for stability.
2. Boost Converter
The boost converter is responsible for stepping up the variable DC voltage produced is to a greater voltage level appropriate for the DC bus.
Inductor and Capacitor: These components store and smooth the energy during the conversion process.
Switching Mechanism: A pulse-width modulation (PWM) signal dynamically adjusts the converter's operation to maintain a consistent output voltage.
Output: A stable DC voltage optimized for integration into the microgrid.
3. Bi-directional DC-DC Converter
This converter regulates the energy flow between the DC bus and the energy storage system (ESS). It operates in two distinct modes:
Buck Mode: Reducing the DC bus voltage when too much energy is being generated in order to charge the battery.

Boost Mode: Increases the battery's output voltage to provide energy to the DC bus during high demand or low-generation periods.
Output: Bi-directional energy flow that balances the supply-demand dynamics.
4. Energy Storage System (ESS)
The ESS, typically comprising lithium-ion batteries or similar technologies, contributes a vital part in ensuring the consistency of microgrid. It stores surplus energy generated by the renewable sources and supplies it during periods of low generation.
State of Charge (SOC) Monitoring: Tracks the battery's charge level to prevent overcharging or deep discharge.
Voltage and Current Sensors: Monitor energy flow for precise control.
Output: A consistent power source for the DC bus during energy deficits.
5. Maximum Power Point Tracking (MPPT)
By ensuring that sustainable energy sources run at their maximum power point, the MPPT controller maximizes their performance.
Algorithm: Adjusts the point of operation of the wind turbines or solar panels to extract the highest possible power.
Control Signal: gives the boost converter feedback for adjustments.
Output: Maximized energy extraction from sources that are renewable.
6. DC Bus
The DC bus acts as the central hub where power from all sources is aggregated, regulated, and distributed to connected loads.
Voltage Regulation: Ensures a stable DC voltage level across the entire microgrid.
Output: A uniform DC voltage available for powering loads.
7. Load Subsystem
The load subsystem includes various devices and systems that consume power from the microgrid. In a DC microgrid, loads are designed to operate directly on DC power, eliminating unnecessary conversion stages.
Dynamic Load Management: Prioritizes power delivery to essential loads during low energy availability.
Output: Energy consumption by connected devices, ensuring operational efficiency.
The DC microgrid block diagram shown in fig.1. illustrates the seamless integration of renewable energy generation, power conversion, energy storage, and load management. Each component is essential to maintain stability, optimizing energy utilization, and ensuring uninterrupted power supply, making the system a sustainable and efficient solution for modern energy challenges.

V. MATLAB SIMULINK SOFTWARE SIMULATION
The simulation diagram of the DC-DC Microgrid system is as shown in the fig.2. This circuit diagram represents the core components of a DC-DC Microgrid system.

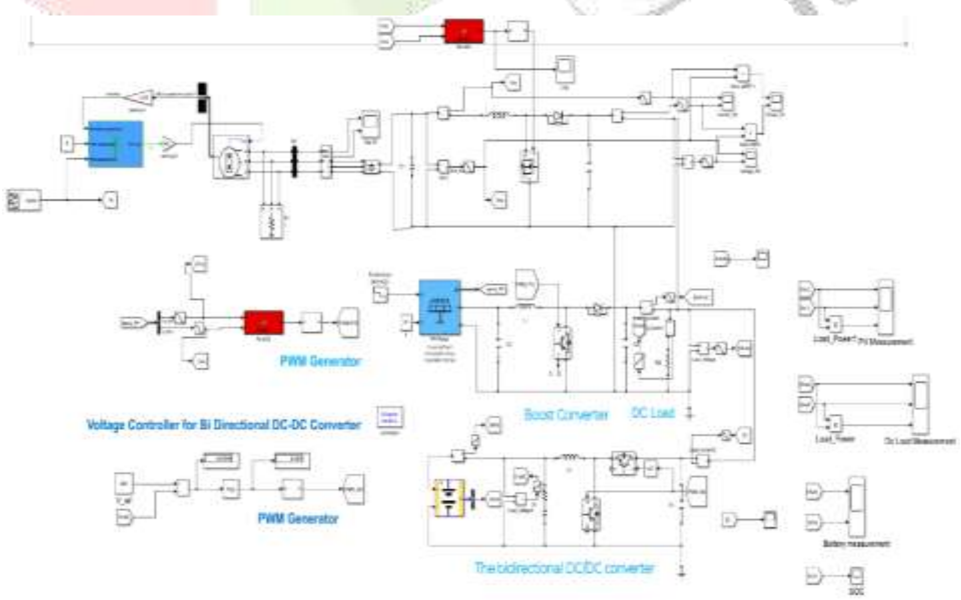

Fig. 2. Simulation using MATLAB SIMULINK Software.

DC microgrids are advanced devices made to control energy storage, integrate renewable energy sources, and guarantee dependable power distribution.

- Wind Turbine Subsystem

Converts wind energy into electrical energy by leveraging the kinetic energy of moving air.
Inputs:
Wind Speed: Determines available energy; higher speeds yield more power.
Pitch Angle Control: Adjusts blade angles to optimize power and protect the turbine.
Components:
Generator Speed Controller: Maintains optimal rotational speed.
Power Extraction Block: Converts mechanical energy into electrical energy.
Purpose: Dynamically adapts to environmental conditions for consistent energy production.

- Photovoltaic (PV) Subsystem

This subsystem captures solar energy and converts it into DC electricity.
Inputs:
Irradiance: Higher solar intensity results in greater output.
Temperature: Affects efficiency; excessive heat reduces performance.
Components:
PV Panel Block: Represents electrical behaviour of solar panels.
Current and Voltage Measurements: Ensure proper operation.
Purpose: Efficiently converts sunlight into clean electricity for the microgrid.

- Boost Converter

A power electronics device that stabilizes the variable DC voltage from renewable sources.
Components:
Inductors and Capacitors: Store and smooth energy.
Switches (MOSFETs) and Diodes: Control and direct current flow.
Control Mechanism: Uses pulse-width modulation (PWM) signals from the Maximum Power Point Tracking (MPPT) system to maintain desired output voltage.
Purpose: Steps up DC voltage to a stable level, ensuring consistent operation.

- Bi-Directional DC-DC Converter

Facilitates energy exchange between the microgrid and the energy storage system (ESS) that uses batteries.
Modes:
Buck Mode: lowers the DC voltage during surplus generation in order to charge the battery.
Boost Mode: Increases battery output voltage during high demand.
Components:
Inductors and Capacitors: Regulate current flow.
Switches and Control Logic: Manage energy flow efficiently.
Purpose: Optimizes battery usage and extends its life by preventing overcharging or deep discharge.

- Battery Subsystem

Stores excess renewable energy and supplies power during low generation.
Components:
Voltage and Current Sensors: Monitor the battery's state.
State of Charge (SOC) Block: Tracks battery charge levels.
Purpose: Ensures uninterrupted power supply and stabilizes the microgrid by compensating for supply-demand fluctuations.

- Maximum Power Point Tracking (MPPT)

Enhances energy extraction from renewable sources.
Components:
MPPT Algorithm: Uses techniques like Perturb and Observe or Incremental Conductance to identify the optimal power output point.
Control Signal: Generates PWM signals for the boost converter.
Purpose: Maximizes efficiency under varying environmental conditions.

- Pulse Width Modulation (PWM) Generators

  Generate high-frequency control signals for power converters.

Components:
Voltage Controllers: Generate error signals.
PWM Blocks: Convert errors into control pulses.
Purpose: Precisely control converters for stable voltage and energy flow.

- Voltage and Current Measurement Blocks

Monitor system performance and provide real-time feedback.
Components:
Voltage Sensors: Measure output voltage.
Current Sensors: Detect anomalies or inefficiencies.
Purpose: Enable dynamic adjustments for optimized performance and safety.

- Load Subsystem

Represents energy consumption in the microgrid.
Components:
DC Load Block: Simulates real-world loads.
Power Measurement Blocks: Monitor energy usage.
Purpose: Ensures reliable energy distribution to meet demand.

- State of Charge (SOC) Monitoring

Tracks battery charge levels for efficient energy management.
Components:
SOC Algorithm: Estimates charge levels based on voltage, current, and time.
Purpose: Prevents overcharging and deep discharge, enhancing battery longevity and system reliability.

By combining energy storage, modern power management technologies, and renewable energy sources, the DC microgrid ensures efficient, reliable, and sustainable power delivery. Each subsystem—from energy conversion to storage and load management—plays a critical role in addressing modern energy challenges.

VI. ALGORITHM

This algorithm implements the Perturb and Observe method, commonly used in Maximum Power Point Tracking (MPPT) for optimizing power output.

Step 1. Initialize Persistent Variables:

If `Vold`, `Pold`, or `Dold` are uninitialized (empty), set:

- `Vold = 0`
- `Pold = 0`
- `Dold = Dinit`

Step 2. Calculate Current Power and Voltage Changes:

- Compute the instantaneous power: `P = V * I`
- Compute the changes in voltage and power:
    - `dV = V - Vold`
    - `dP = P - Pold`

Step 3. Determine the Change in Duty Cycle (`D`):

- If `dP < 0` (power decreases):
    - If `dV < 0` (voltage decreases): Decrease duty cycle: `D = Dold - deltaD`
    - Else (voltage increases): Increase duty cycle: `D = Dold + deltaD`
- Else (`dP >= 0`, power increases):
    - If `dV < 0` (voltage decreases): Increase duty cycle: `D = Dold + deltaD`
    - Else (voltage increases): Decrease duty cycle: `D = Dold - deltaD`

Step 4. Clamp Duty Cycle Within Limits:

- If `D` exceeds `Dmax` or is below `Dmin`, revert to the previous duty cycle: `D = Dold`

Step 5. Update Persistent Variables:

- Save the current values for use in the next iteration:
    - Dold = D
    - Vold = V
    - Pold = P

Step 6. Return the Updated Duty Cycle (`D`)

VII. RESULTS AND DISCUSSION

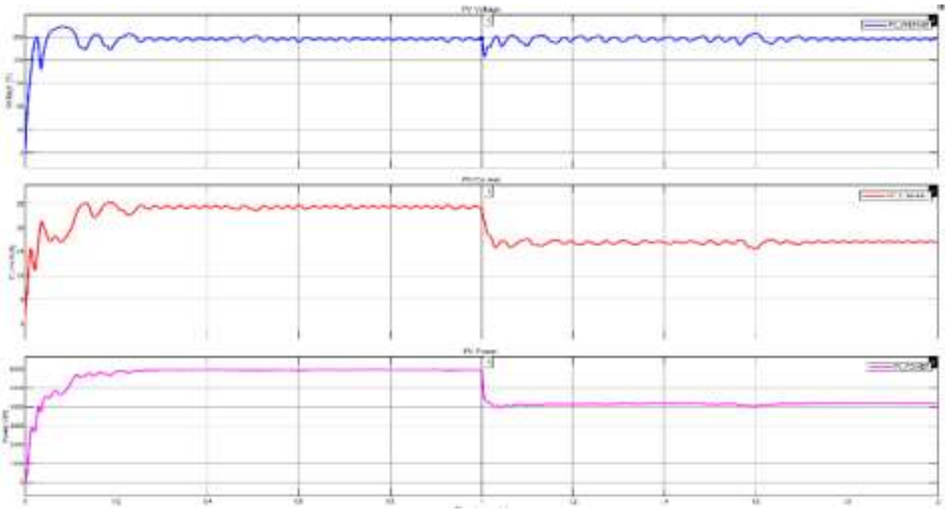

Fig.3. Output of PV Array system in Simulation

The output voltage from solar energy is about 250V, which is shown in Fig.3. We can observe that we got 6kW of power for 24A of current.

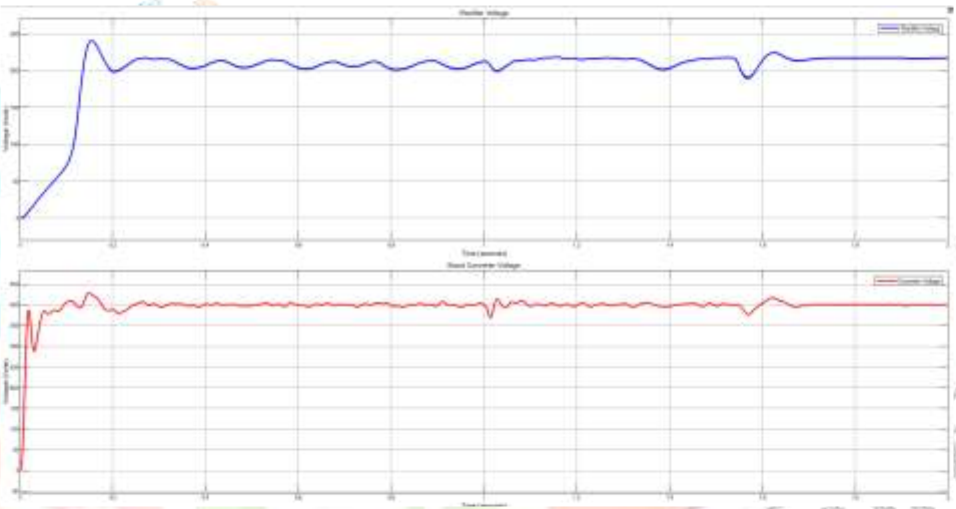

Fig.4. Output of wind turbine in Simulation

In the Fig.4., we can observe that the rectified output voltage of 220V is further boosted to 400V.

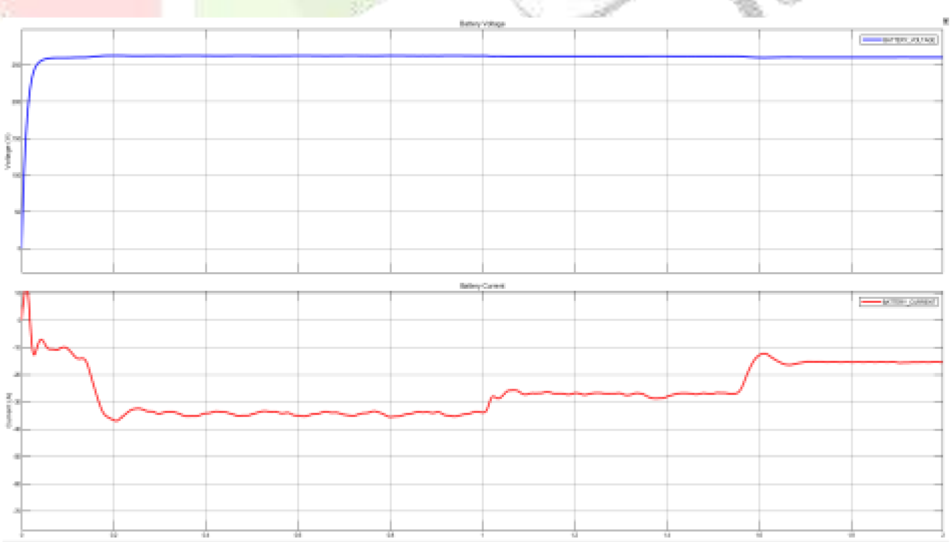

Fig.5. Output of Battery in Simulation

In the Fig.5. we can observe that the Battery voltage is constantly maintained for 260V, charges for first 1.6 seconds and then starts discharging after 1.6 seconds.

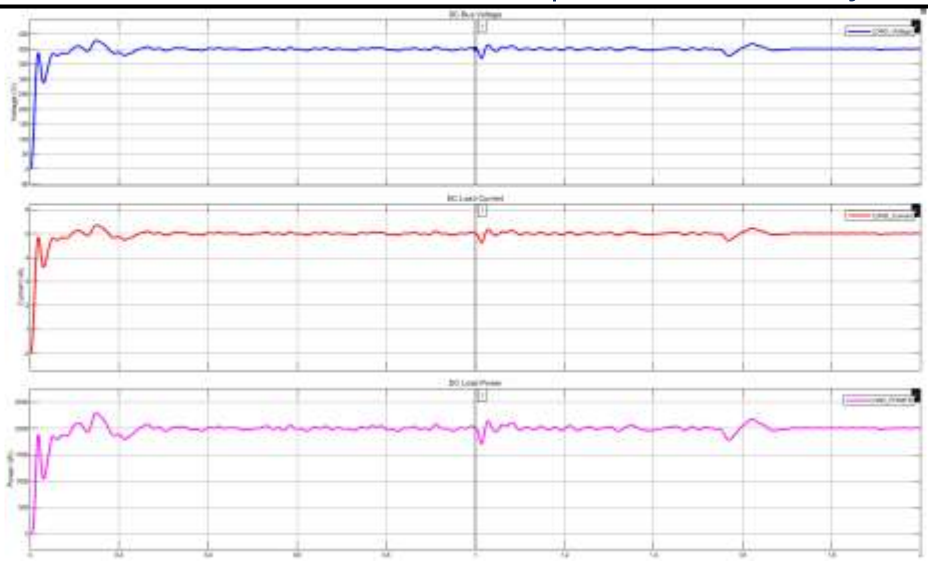

Fig.6. Output of the DC Grid in Simulation

It is evident in fig.6. that the DC Micro grid's output voltage is kept at 400V with a 2kW power rating. The output is maintained constant irrespective of variation in wind factor and irradiance factor with the help of BESS (Battery Energy Storage System).

VIII. CONCLUSION

This paper examines a DC micro grid's design and simulation analysis, underlining how revolutionary it may be for the integration of sources of clean energy. The micro grid is sustained by wind and solar power.as its main power sources, using a boost converter to maintain a steady DC bus voltage of 400V. This consistent voltage ensures reliable power for connected devices, even when energy generation fluctuates. By managing the battery storage system's charging and discharging, enabling efficient application of stored energy when required. The system incorporates a Maximum Power Point Tracking (MPPT) algorithm to optimize the energy harvested from renewable sources. This algorithm adjusts to variations in sunlight and winds so as to ensure optimal operation of the system. The study highlights several advantages of DC microgrids, such as fewer energy losses, easier control systems, and seamless integration of renewable power with energy storage. These benefits make DC microgrids a practical solution for modern energy challenges, whether for remote communities or urban centers. Simulation results show the system maintains stable voltage and provides uninterrupted power, even under varying conditions, proving its reliability and effectiveness. By addressing challenges like energy security and the variability of renewable energy, this work positions DC microgrids as a sustainable and efficient alternative to traditional AC systems. The findings demonstrate how DC microgrids can meet the growing demand for clean, reliable energy while reducing environmental impact and supporting a greener future

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