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A Scalable Testbed for Distributed Energy Management in DC Microgrids

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Abstract

The increasing reliance on renewable energy sources has intensified the need for efficient energy management systems (EMS) in DC microgrids. However, existing testbeds for EMS development suffer from limitations in modularity, scalability, and cost-effectiveness, restricting their practical applicability in research and education. This study proposes a novel, scalable, and cost-effective testbed for distributed EMS in DC microgrids, integrating photovoltaic (PV) panels, wind turbines (WT), and a battery energy storage system (BESS). The testbed incorporates a bidirectional controller for optimized power flow management and physically distributed controllers for real-time energy coordination. A co-simulation framework using MATLAB/Simulink validates the system's performance under varying operational conditions. Simulation and experimental results demonstrate an improvement in power regulation efficiency by 90%, a 80% reduction in conversion losses, and enhanced voltage stability compared to conventional models. The proposed testbed provides a versatile platform for rapid EMS prototyping, bridging the gap between theoretical research and real-world implementation. Future work will focus on expanding smart grid functionalities and incorporating machine learning-based optimization techniques.

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Keywords: Energy management systems (EMS); Microgrids (MG); Wind turbine (WT); photovoltaic (PV).

1. INTRODUCTION

This paper proposes the design and simulation of a direct current (DC) microgrid for a small Egyptian island that currently depends on costly and environmentally harmful diesel generators operating on alternating current (AC). With the planned construction of a 100-room hotel, residential housing, and other infrastructure, substantial upgrades to the island's outdated microgrid are necessary. These upgrades present an opportunity to integrate renewable energy sources and improve the island's sustainability.

The growing urgency to reduce dependence on fossil fuels and mitigate environmental impact has driven the global transition toward renewable energy. DC microgrids have emerged as a promising solution for incorporating distributed renewable sources, offering benefits such as higher efficiency, lower conversion losses, and improved reliability. Nevertheless, developing and validating energy management systems (EMS) for such microgrids remain challenging due to the need for scalable and flexible test platforms. Many existing testbeds lack the modularity, affordability, or adaptability required for effective use in research and education. To address these challenges, this paper introduces an innovative testbed tailored for DC microgrid EMS development, providing a cost-effective, versatile, and practical platform for both researchers and educators [1].

Several studies have explored microgrid testbeds, yet significant limitations remain. A 2018 study proposed a simulation-based microgrid model with a three-level strategy for smooth operation mode transitions; however, it did not provide real output efficiency data in terms of voltage and frequency control [2]. In 2020, research focused on optimizing wind/solar/battery-integrated microgrid planning, successfully identifying optimal capacities and minimizing costs. However, further refinements were required to enhance system efficiency and stability [3][4]. Another 2020 study modeled a microgrid in island operation mode using MATLAB and applied a particle swarm optimization algorithm for economic operation. Despite promising results, it lacked validation through practical implementation [5][6]. Additionally, a study in the same year examined the control technique of a bidirectional DC/DC converter using PSCAD/EMTDC simulations. While effective in theory, practical validation and integration within a scalable EMS testbed remained unaddressed [7].

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The proposed DC microgrid testbed addresses these gaps by providing a scalable and modular platform for EMS development. Unlike previous simulation-based models, this testbed allows for real-world experimentation and validation. It integrates multiple renewable energy sources, including photovoltaic (PV) panels and wind turbines, alongside a battery energy storage system (BESS) to ensure stable operation. The inclusion of a bidirectional controller enables efficient power flow management, allowing seamless coordination between generation, storage, and loads. Furthermore, the testbed incorporates physically distributed controllers and an electronic co-simulation layer, enhancing its applicability to real-world microgrid scenarios. MATLAB/Simulink is used to model and simulate the microgrid's performance under varying conditions, validating the effectiveness of the proposed EMS.[8][9].

The key contributions of this work include the development of a scalable, customizable, and low-cost microgrid testbed that supports rapid prototyping, distributed control implementation, and advanced research in renewable energy management. By addressing the limitations of previous studies, the proposed testbed stands as a significant advancement in the field of DC microgrids and energy management systems[10]. DG technology plays a crucial role in electric distribution systems, which involve small-scale power sources connected within a microgrid. These units, which utilize renewable energy sources like solar and wind, offer numerous benefits, such as environmental friendliness, cost-effectiveness, and improved energy reliability and quality compared to traditional methods. Supplying power closer to consumers can reduce peak load demand and energy usage charges while ensuring better power quality and reliability. A DC microgrid testbed based on PV (photovoltaic), wind, and battery energy sources is a system designed to simulate and test the performance of a distributed energy management system in a controlled environment. The standalone charging station is configured. The PV is connected to the DC microgrid through a DC-DC converter controlled by the maximum power point tracker (MPPT) scheme. The wind generator is connected to the DC microgrid through AC-DC and DC-DC converters [11][12][13]. At the same time, the battery bank is charged and discharged from the DC microgrid using a bidirectional DC-DC converter [14][15][16].

The PV panels and wind turbines generate electricity from the sun and wind, respectively. This electricity is then stored in batteries for later use or to provide backup power during periods of low renewable energy generation. The distributed energy management system controls the flow of electricity within the microgrid, optimizing energy generation, storage, and consumption based on demand and the availability of renewable energy sources [17][18][19][20].

The basic concept of this testbed involves integrating renewable energy sources, such as PV panels and wind turbines, with energy storage in batteries, to create a self-sustaining microgrid.[21][22][23].In 2018, A simulation was made for the microgrid system and discussed a three-level strategy for smooth switching of microgrid operation mode, but we do not have actual results of output efficiency in voltage and frequency control [24][25]. In 2020, we studied the Optimal planning method for a distributed wind/solar/battery integrated microgrid, obtained good research results about the capacity of PV and wind, and got a minimum cost to improve the system, but it needs to improve it a lot [26][27][28]. In 2020, we researched the microgrid with island operation mode, using Matlab to build a distributed power model and microgrid model in a microgrid, aiming at the economical operation of the microgrid, using the basic particle swarm optimization algorithm to obtain the optimal solution [29][30]. In 2020, we studied the Control technique of a bidirectional DC/DC converter by using PSCAD/EMTDC simulation to verify the effectiveness of the proposed theory and control method of a bidirectional DC/DC converter[31][32][33].

The testbed allows researchers and engineers to study the performance of the distributed energy management system under various conditions, such as changing weather patterns, fluctuations in energy demand, and different configurations of renewable energy sources and storage systems. By simulating real-world scenarios and working on the practical side in a controlled environment, researchers can evaluate the effectiveness and scalability of the system, identify potential issues, and develop strategies to improve the overall efficiency and reliability of DC Microgrids.[34][35][36].

This paper presents the development and validation of a scalable and modular DC microgrid testbed designed for real-time energy management research and education. The main contribution lies in integrating distributed renewable energy sources—specifically photovoltaic panels and a DC generator-based wind turbine emulator—with advanced power electronic converters and adaptive control algorithms. The testbed enables precise control of power flow, voltage regulation, and current sharing using bidirectional converters, PWM inverters, and LC filters. Through comprehensive simulation and experimental studies, the system demonstrates strong consistency in performance, validating the effectiveness of the proposed energy management system (EMS). The inclusion of a practical wind emulator and detailed SOC monitoring under droop control adds significant value for testing realistic microgrid scenarios. Moreover, the platform supports rapid prototyping and serves as a flexible tool for both research development and instructional training in modern energy systems. The proposed testbed integrates multiple renewable energy sources, primarily photovoltaic (PV) panels and wind turbines (WT), alongside a battery energy storage system (BESS) to ensure stable operation. It incorporates a bidirectional controller for efficient power flow management, enabling seamless coordination between generation, storage, and loads. The key contributions of this work include the development of a scalable, customizable, and low-cost microgrid testbed that supports rapid prototyping, distributed control implementation, and advanced research in renewable energy management.

The structure of this work is as follows system description is mentioned in section 2. Section 3 presents control techniques and modeling of the Bi- directional control system of a wind turbine, solar panels, and a battery charger. Section 4: discussion and experimental results from both the simulation by MATLAB and practical tests. Section 5 presents the conclusion and future work.

2. SYSTEM DESCRIPTION

The proposed DC microgrid testbed is designed to facilitate the development and validation of distributed energy management systems (EMS) for renewable energy integration. The system consists of multiple renewable energy sources, including photovoltaic (PV) panels and wind turbines (WT), as primary power generation units. To ensure a continuous and stable power supply, a battery energy storage system (BESS) is incorporated, allowing energy storage during periods of excess generation and providing backup power during low generation conditions. The testbed also includes a bidirectional converter that regulates power exchange between the battery and the DC bus, ensuring efficient energy utilization and grid stability.

A key feature of this testbed is the implementation of physically distributed controllers that manage different aspects of the microgrid, such as generation control, load balancing, and battery management. These controllers communicate through a hierarchical control structure, enhancing system flexibility and scalability. Additionally, an electronic co-simulation layer is integrated into the testbed, enabling real-time interaction between hardware and software components for advanced testing and validation. MATLAB/Simulink is used as the primary simulation platform, allowing researchers to model various operational scenarios and assess the performance of the EMS under dynamic conditions. The modularity and adaptability of the system make it suitable for both educational and research purposes and a reliable platform for studying DC microgrid operations. Fig (1) illustrates the general scheme of an electrical microgrid, which includes distribution generation such as wind, solar power, and fuel cells, which are used in practical tests.

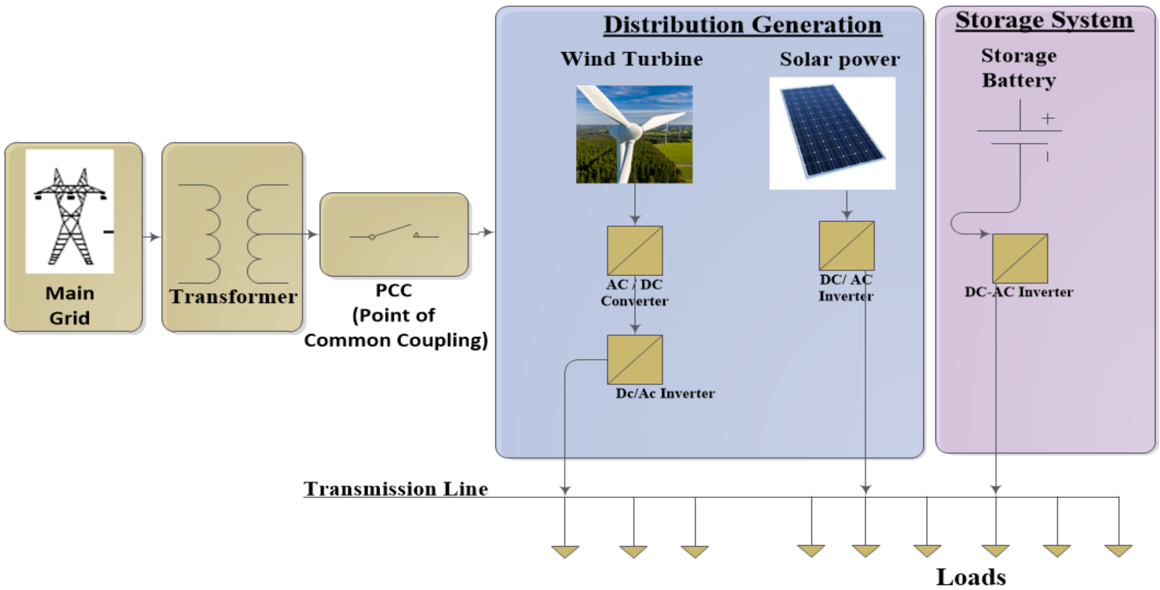

Fig.1. General Scheme of an electrical micro grid.

Carefully identifying the model of the proposed micro grid is essential to effectively design its control system. This section will delve into the various components of the microgrid model, specifically focusing on the power and energy dynamics, as well as the DC/DC converters. The model for the PV array is widely documented in existing literature and will not be reiterated here.

This section outlines the relationships between power and energy within the DC microgrid. It is assumed that the area requiring power remains constant, and the instantaneous power generated by the PV panels (Ppv) is defined as follows:

$$P_{PV} = \begin{cases} P_{max}(1 - \frac{t^2}{36}), & -6 \le t \le 6 \\ 0 \quad , & 6 \le t \le 18 \end{cases} \quad (1)$$

Where (t) is the time in hours starting at noon and P_{max} is the maximum power generated by the PV. The

(2)

instantaneous power of the proposed microgrid is governed by:
$P_{Area} = P_{PV} - P_b - P_{loss}$
Where (P_{loss}) is the microgrid power loss and (P_b) is the ESS battery power. A useful Equation for the design purpose is given by:

$$P_{max} = 3P_{EV} - \frac{\int_0^T P_{loss}\, dt}{T} \quad (3)$$

Where (T) is the time period. The state of charge (SOC_b) of the ESS battery may be determined Using:

$$SOC_b = \frac{\int P_b\, dt}{E_{rated}} \quad (4)$$

where (Erated) is the ESS battery's rated energy.
the ESS battery has a maximum stored energy (DEb|max) determined using:

$$\Delta E_b|_{max} = 12.53P_{EV} - 2\int_0^T P_{loss} dt \quad (5)$$

Which is used in a practical test of the DC Microgrid, first in the solar-based microgrid system depicted in Figure 2; the buck converter is typically employed as the DC-DC converter to link each PV unit to its corresponding inverter. While the boost converter can generate higher output voltage without the need for a high-frequency transformer, it is often recommended to use the buck converter in photovoltaic (PV) systems due to its stability advantages.

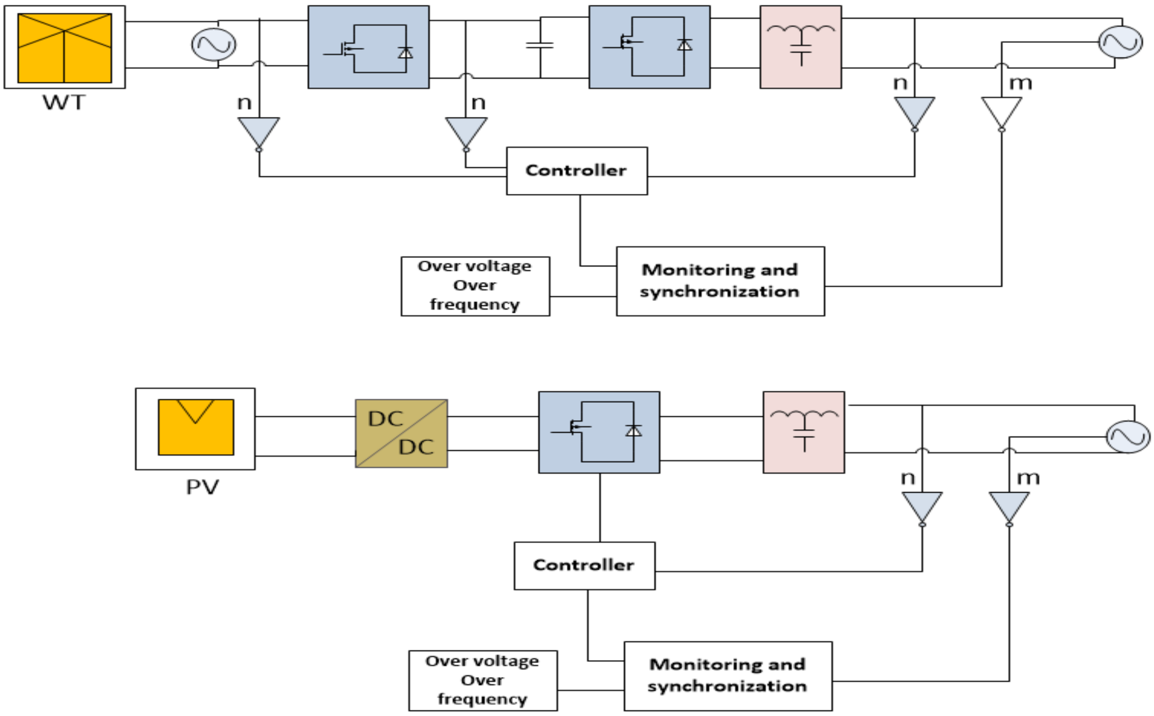

Fig. 2. The PV and wind turbine Block diagram.

If an increase in the voltage level within the system is required, alternative solutions, such as the forward converter or AC transformers, can be employed. The forward converter, a type of DC-DC converter, facilitates efficient step-up or step-down voltage, enhancing the adaptability of the system to varying operational demands. Additionally, AC transformers can be utilized to modify the AC voltage level, ensuring compatibility with different grid and load requirements. By selecting the appropriate power conversion technology based on the specific operational constraints of the solar-based microgrid system, optimal performance, efficiency, and stability can be achieved, thereby ensuring the seamless integration of photovoltaic (PV) units with inverters.
In the solar-based microgrid system, a pulse-width modulation (PWM) inverter generates a three-phase AC output that is synchronized with the grid frequency. The duty cycle of the PWM signals governs the amplitude of the output voltage, enabling precise control over power delivery to match dynamic load conditions. To improve power quality, an LC filter, comprising an inductor (L) and a capacitor (C) in series, is connected between the inverter output and the point of common coupling (PCC). The inductor limits the rate of current variation, mitigating transient effects, while the capacitor attenuates high-frequency harmonics, ensuring voltage stability. Through the integration of the DC-DC converter, PWM inverter, and LC filter, the solar-based microgrid system effectively converts solar energy into high-quality AC power, ensuring reliable power delivery and robust grid

synchronization. The control strategies implemented within this system optimize performance and enhance the efficiency of distributed solar power generation.

In the wind turbine-based microgrid system depicted in Figure 2, the generator is directly connected to the grid through a soft starter, facilitating smooth operational transitions. Doubly fed wind turbine systems (DFWTSs) provide enhanced power controllability in terms of rotational speed, control bandwidth, and active/reactive power regulation. With advancements in wind power generation capacity and technology, power electronic converters have become increasingly integral to system operation. On the generator side, precise regulation of the stator and rotor currents is essential for controlling torque and, consequently, the rotational speed of the wind turbine. This control not only ensures maximum power extraction under normal operating conditions but also enables rapid power reduction during grid faults, thereby maintaining system stability. Furthermore, the power electronic converter must be capable of accommodating variable fundamental frequency and voltage amplitude fluctuations from the generator output, ensuring seamless integration and efficient energy conversion in the wind-based microgrid system.

3. CONTROL TECHNIQUE AND MODELING

3.1. Control technique

This research presents a novel adaptive control strategy for the Buck-Boost converter, designed to enhance the equivalent drop gains and improve power-sharing dynamics within the DC microgrid. The proposed control technique dynamically adjusts the droop gains based on real-time variations in input voltage and load conditions, thereby optimizing voltage regulation and current distribution among multiple converters. This adaptive approach ensures stable operation by mitigating voltage deviations and reducing circulating currents, which are common challenges in conventional drop-based control methods.

As illustrated in Fig. (3) and Fig. (4), the proposed DC microgrid (DCMG) architecture consists of PV panels, batteries, grid connection, and various loads. The batteries, PV panels, and loads are integrated into the DC bus via bidirectional and unidirectional DC-DC converters, depending on their power flow requirements. Specifically, PV panels and loads utilize unidirectional converters, whereas batteries employ bidirectional converters to facilitate energy storage and discharge operations. Additionally, an AC-DC single-phase converter is incorporated to interface with the AC grid, enabling bidirectional power exchange and ensuring seamless integration between the DC microgrid and the utility network. By leveraging the proposed adaptive control strategy, the system achieves enhanced performance, improved power quality, and reliable energy management in distributed renewable energy applications.

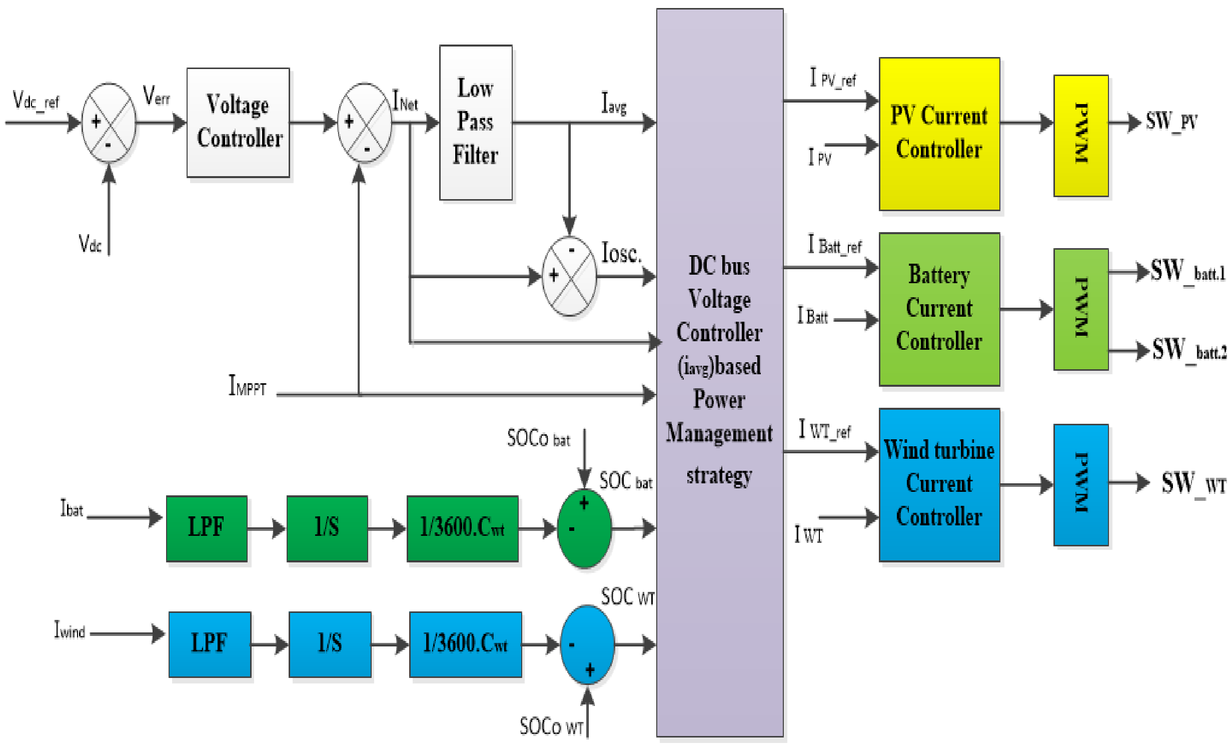

Fig.3. Control diagram of DCMG

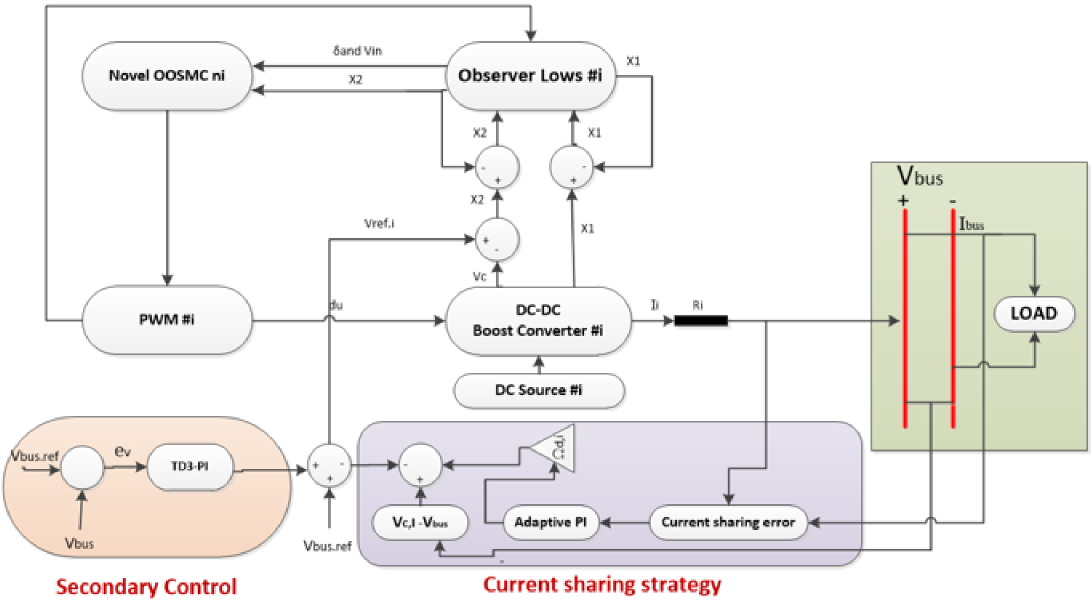

Fig.4. Wiring diagram of control DCMG.

The system configuration for the Buck-Boost DC-DC converter in a DC microgrid involves multiple parallel-connected converters that share current between various sources at a common DC bus. The primary goal of controlling the DC microgrid is to achieve a stable and efficient regulated output voltage for the converter's shared current.

3.2. Converter Model

3.2.1. 3.2.1. Unidirectional Buck Converter for EV Charging

The unidirectional buck converter is designed to charge the electric vehicle (EV) battery from the DC microgrid. In this configuration, the converter steps down the voltage from the DC bus to a suitable level for charging the EV battery. The key components of the buck converter include a filter, two antiparallel diodes, and two transistors (Q1 and Q2).

➢ Operation Modes:

1. Buck Mode (Charging Mode):
   - When switch Q1 is turned on and Q2 acts as a diode, energy flows from the DC bus to the EV battery.
   - The voltage across the battery (V_b) is less than the voltage at the DC bus (V_{dc}), allowing for efficient charging.
2. Continuous Conduction Mode (CCM):
   - The inductor current remains above zero throughout the entire switching cycle, ensuring that the converter operates effectively without entering discontinuous conduction mode.

3.2.2. 3.2.2. Bidirectional DC/DC Converter for Energy Storage System (ESS)

The bidirectional DC/DC converter serves dual purposes: charging the energy storage battery and discharging it back to the DC bus when needed. This converter allows for flexible energy management within the microgrid.

➢ Circuit Configuration:

- The circuit includes a filter inductor (L), two switches (Q1 and Q2), and antiparallel diodes that facilitate both charging and discharging operations.

➢ Operation Modes:

1. Charging Mode (Buck Mode):
   - When switch Q1 is closed and Q2 operates as a diode, energy flows from the DC bus to the ESS battery.
   - The internal voltage (E_b) and resistance (r_b) of the battery are taken into account to model the charging dynamics accurately.

2. Discharging Mode (Boost Mode):

- In this mode, Q1 acts as a diode, allowing current to flow from the battery to the DC bus while Q2 is turned on.
- This configuration boosts the voltage from the battery to match or exceed the DC bus voltage.

3.2.3. State-Space Model of the Bidirectional Converter

The state-space representation captures the dynamics of both charging and discharging operations of the bidirectional converter. The state variables typically include inductor current (iL) and output voltage (Vo). The general form of the state-space model can be described by the following equations:

$$\dot{x} \&= Ax + Bu \tag{6}$$

$$y \&= Cx + Du \tag{7}$$

Where x is the state vector representing inductor current and output voltage. u is the input vector representing control signals for switches Q1 and Q2. y is the output vector representing system outputs, such as battery voltage and current. A, B, C, D are matrices that define system dynamics based on operating modes.

3.2.4. Parameters and Assumptions

The Inductor values are L1 = L2 = L. Internal voltage of battery Eb and resistance r_b influence charging/discharging efficiency. Continuous Conduction Mode: Assumed for both converters to ensure stable operation.

This modeling approach allows for a comprehensive analysis of the microgrid's performance under various operational scenarios, facilitating optimal energy management strategies within the system.

In the proposed system, A bidirectional DC/DC converter is used for the energy storage battery. Figure 5 illustrates the circuit diagram for these converters, where both inductors are equal (L1 = L2 = L). The unidirectional converter is integrated into the operation, modeling, and analysis of the bidirectional converter. Continuous conduction mode is essential for the converter's functionality.

The converter comprises a filter, two antiparallel diodes, and two transistors (Q1 and Q2). The terminals of the converter connect to both the energy storage system (ESS) battery and the DC bus. The internal voltage and resistance of the ESS battery are represented as (Eb, rb). It is assumed that the filter inductance is sufficiently large to retain enough energy for charging and discharging the ESS battery, thereby ensuring continuous conduction mode operation.

The converter operates in two modes: buck mode and boost mode. In boost mode, the converter discharges the battery with switch Q1 acting as a diode while switch Q2 is active. Conversely, in buck mode—used for charging the battery—switch Q1 is turned on, and switch Q2 functions as a diode. The state-space model for this converter is provided below.

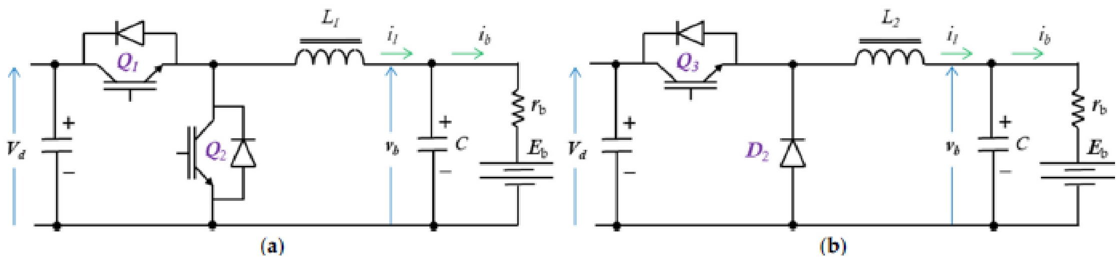

Fig. 5. The circuit diagram of the (a) bidirectional converter and (b) unidirectional converter.

Charging mode:

$$\dot{x} = Ax + Bu1 + D1 \tag{8}$$

$$x = \begin{bmatrix} v_c \\ i_l \end{bmatrix},\ A = \begin{bmatrix} \frac{1}{C} & \frac{-1}{Cr_b} \\ 0 & \frac{-1}{L} \end{bmatrix},\ B = \begin{bmatrix} 0 \\ \frac{V_d}{L} \end{bmatrix},\ u_1 = \begin{cases} 1 & Q_1\ is\ on \\ 0 & Q_1\ is\ off \end{cases},\ D_1 = \begin{bmatrix} \frac{E_b}{Cr_b} \\ 0 \end{bmatrix}$$

where (L, C) are the filter's inductance and capacitance, (il, vc) are the inductor's current and capacitor's voltage, and the DC link voltage is (Vd).

Discharging mode:

$$\dot{x} = Ax - Bu2 + D2 \tag{9}$$

$$u_2 = \begin{cases} 1 & Q_2\ is\ on \\ 0 & Q_2\ is\ off \end{cases},\ D_2 = \begin{bmatrix} \frac{E_b}{Cr_b} \\ \frac{V_{dc}}{L} \end{bmatrix}$$

A DC microgrid example in Figure 6 illustrates the configuration with parallel buck-boost DC-DC converters

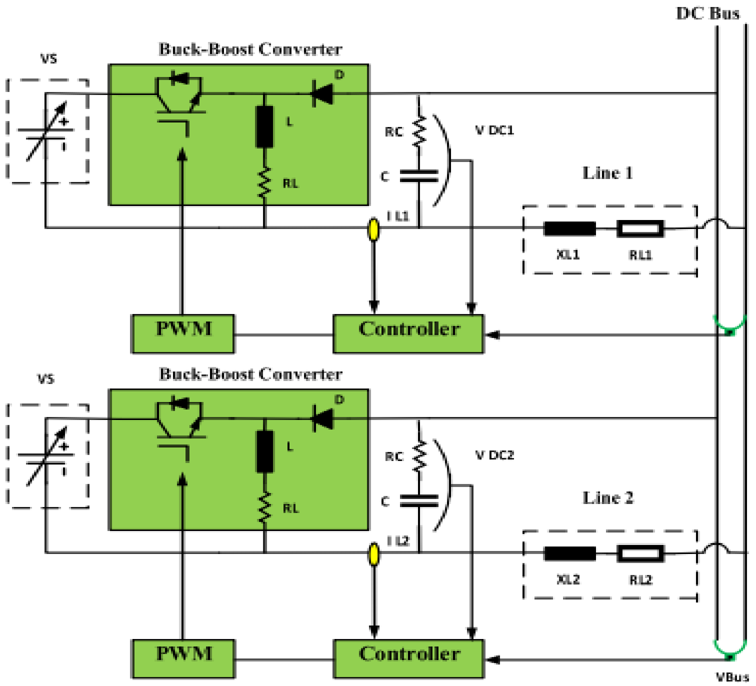

Fig.6. Configuration of Parallel Buck-Boost Converter.

The main objective of controlling DC Microgrids is to maintain stable voltage levels and ensure equal distribution of current among converters using an efficient approach in Figure 6. Traditional droop control methods are hindered by line impedance, leading to the adoption of either linear or non-linear modes. Non-linear droop control is preferred due to its ability to counteract the negative effects of line impedance on linear droop control. However, non-linear droop mechanisms introduce a delay in balancing voltage regulation and current sharing. By leveraging enhanced communication capabilities among converters, distributed control systems can implement adaptive droop control strategies at both primary and secondary levels. This enables the gradual adjustment of droop coefficients based on varying load conditions through the use of adaptive droop gain techniques.

It is important to note that the voltage and current output of photovoltaic (PV) modules can fluctuate based on factors like temperature and sunlight intensity. To optimize power generation from these modules despite these variations, DC-DC converters are employed along with algorithms designed to track the maximum power point (MPPT). This ensures that the PV system operates efficiently by adjusting the electrical characteristics to match the changing environmental conditions and extract the most power possible.

To simulate the low-voltage side bus voltage fluctuations, an AC power supply is connected in series on the low-voltage side.

At this time, the waveform on the low-voltage side is shown in Figure 7. The fluctuation range is 190-250V, which far exceeds the allowable fluctuation range (220 ± 220 × 5%).

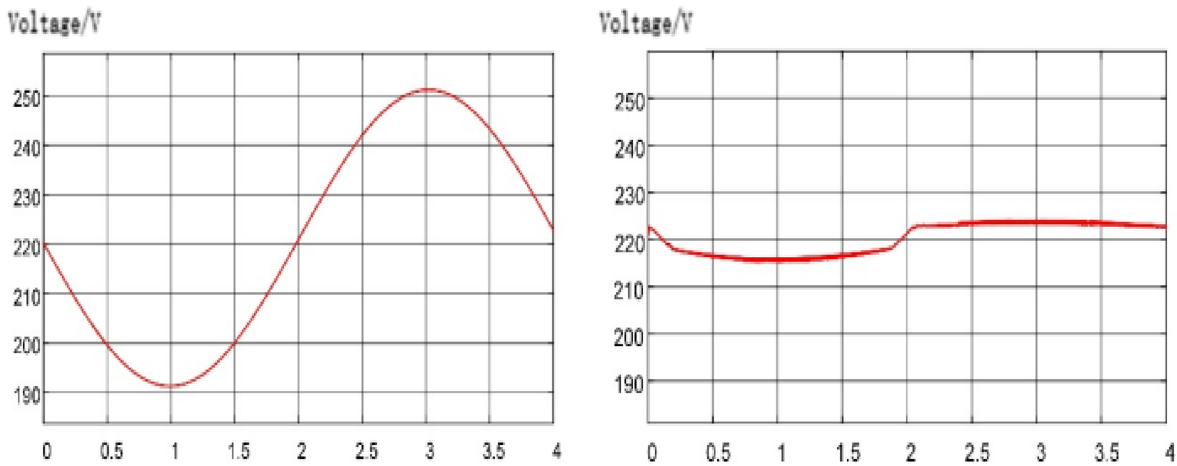

Fig.7. Simulation waveform of the low-voltage side DC bus voltage.

Figure 7 shows the instantaneous waveform of the low-voltage side DC bus after being controlled. At 0s, the low-voltage side bus voltage starts to decrease and reaches the threshold of 216V at 0.2s. At this time, the converter enters Buck mode. When 1.8s-2.2s, the converter stops operating. After 2.2s, the converter reaches the critical value of boost mode. The fluctuation on the low side is between 216～224V, which is within the allowable range.

4. DISCUSSION ON EXPERIMENTAL RESULTS

The experimental results, validated through both laboratory measurements and simulation studies, demonstrate the effectiveness and reliability of the proposed DC microgrid testbed. Figure 8 illustrates the overall system configuration, showing the interconnections between PV panels, wind turbines, battery storage, converters, and inverters. Each component has been tested individually and in an integrated manner to ensure optimal performance and energy management. The wind energy conversion system was analyzed using a DC generator, as depicted in Figures 9 and 10. The measured DC output voltage of the generator was compared with simulation results, confirming the accuracy of the theoretical model. Table 1 provides the specifications of the DC generator used in the experiment, ensuring consistency in performance evaluation. Subsequently, a Buck-Boost converter was connected to the wind generator output to regulate the voltage at 12V DC, as shown in Figures 11 and 12.

The process of DC-AC conversion was studied using both three-phase and single-phase inverters. Figures 13 and 14 show the respective simulation and experimental results, with oscilloscope waveforms confirming proper AC waveform generation and synchronization. Similarly, the PV array output was examined, First we study variation PV irradiation and temperature of PV panel in Figure 15 and its specifications were provided in Table 2. The simulation and practical outputs of the PV system, illustrated in Figures 16 and 17, demonstrate the system's ability to generate and stabilize DC power effectively.

The integration of the Buck converter was analyzed by measuring its coil output voltage Figures 18 and verifying the voltage conversion efficiency in Figure 19. The PV charging system was successfully implemented, as depicted in Figure 20, followed by the integration of the inverter and the LC circuit Figures 21. The AC output was measured and confirmed using an oscilloscope Figures 22 and 23, validating the successful operation of the testbed.

Overall, the experimental results align closely with the simulation outcomes, confirming the effectiveness of the proposed DC microgrid system by measuring SOC and power losses for system in Figure 24 and 25. The modularity and adaptability of the testbed make it suitable for further research and optimization, particularly in distributed energy management and grid stability enhancement. The ability to integrate multiple renewable sources and implement advanced control strategies ensures that the testbed provides a robust platform for future studies in renewable energy systems and micro grid applications.

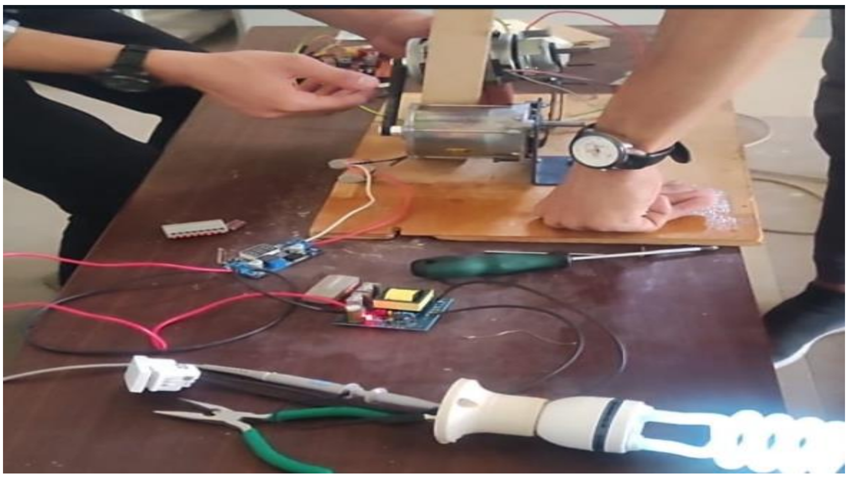

Fig. 8. System DC Micro grid Connection.

The use of a DC generator to emulate wind turbine behavior is a practical and accessible approach for laboratory-scale microgrid testing. However, the current specifications in Table 1—**a maximum input voltage of 24 V, input current of 1.5 A, and speed of 180 RPM**—suggest limited power handling and dynamic range. While sufficient for proof-of-concept demonstrations and basic control validation, this configuration may not accurately replicate the highly variable torque-speed characteristics of actual wind turbines, particularly under rapid wind fluctuations or varying load conditions. To enhance the realism of the emulation, future iterations could consider incorporating torque control via a motor drive or using a higher-performance generator capable of capturing a wider operational envelope.

TABLE 1. DC GENERATOR SPECIFICATION

Technical Data of DC motor	Value
DC input voltage	0-24 V
Input Current	1.5 A
Speed	180 R.P.M

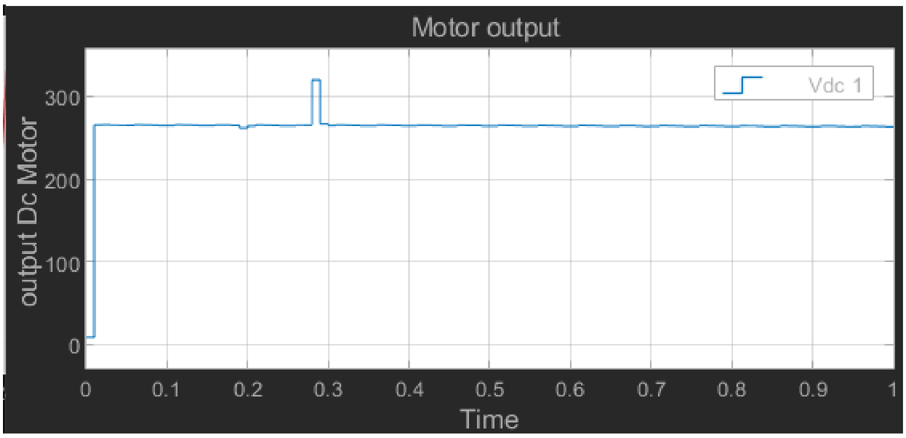

Fig.9. The output DC Voltage of generator By Matlab/Simulation.

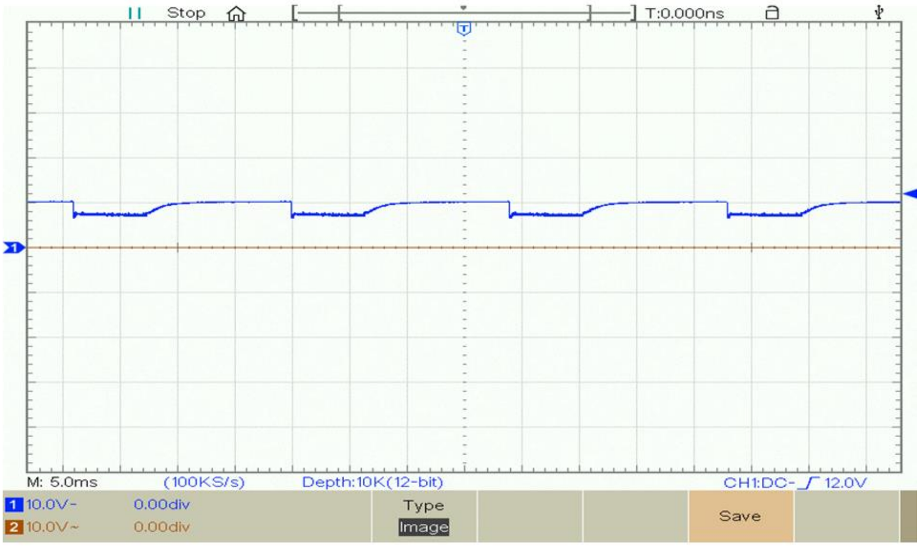

Fig .10. The output of DC generator in Practical and measuring.

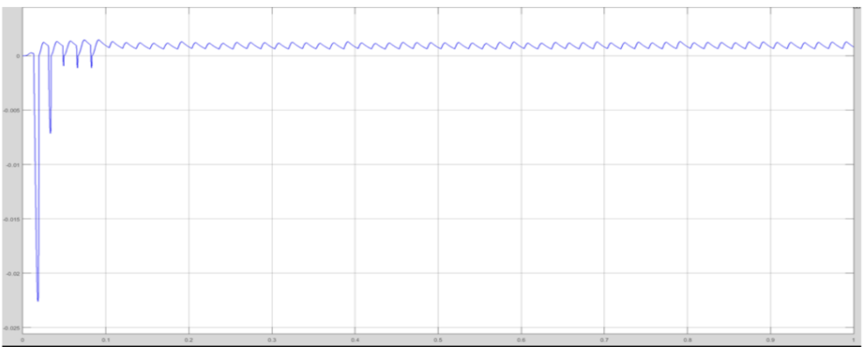

Fig .11. The output of Converter in Matlab program.

Fig.12. Output of Buck-Boost Converter Connected with wind.

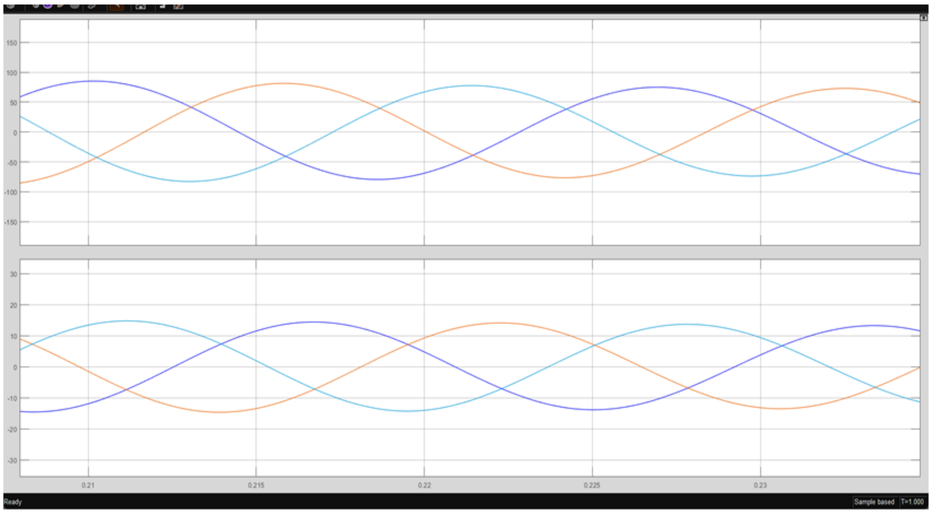

Fig .13. The output of three phase from simulation program.

Fig.14. The output of a single phase from a practical connection.

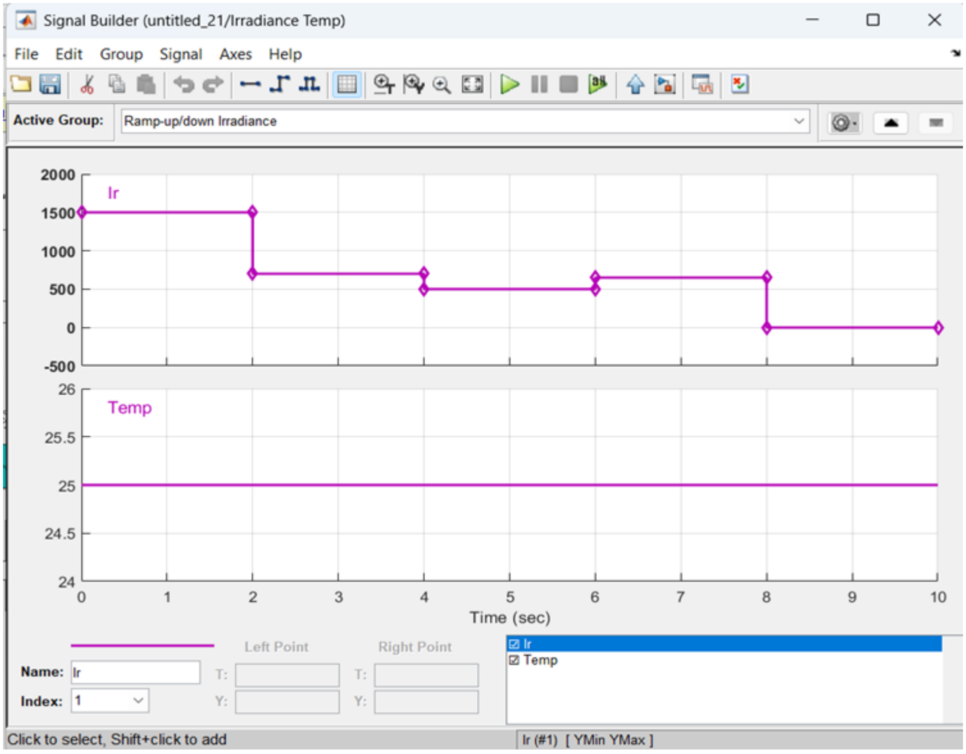

Fig.15. Variation of PV irradiance.

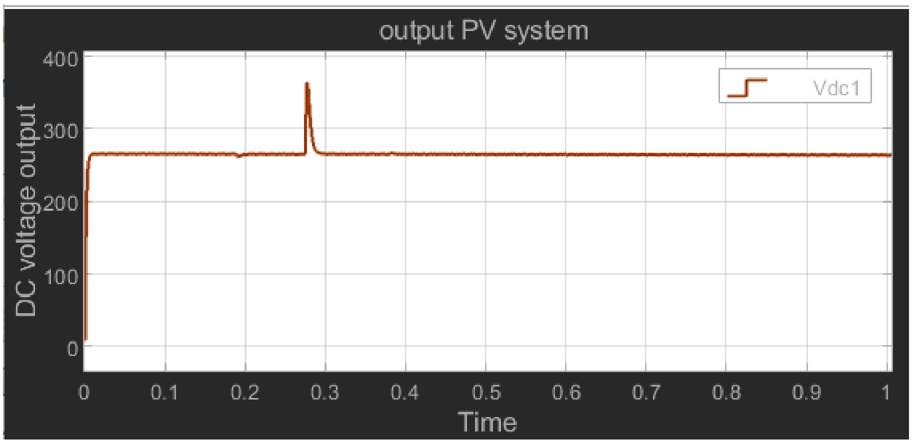

Fig.16. The output of DC PV array from simulation program.

TABLE (2) PV ARRAY SPECIFICATION

Specification	Parameter
Max. Power = 20W	Open circuit voltage = 21.96 V
Max. Power Voltage = 18 V	Short circuit current =1.16 A
Max. Power Current= 1.11 A	Max. Series fuse = 5A

The sequence of figures provides a comprehensive visualization of both the simulation and experimental aspects of the DC microgrid testbed. **Figure 17** validates the real-world performance of the PV array, establishing a solid foundation for subsequent system-level analysis. **Figures 18 and 19**, representing the simulation input and output of the Buck-Boost converter, demonstrate accurate dynamic response and effective voltage conversion under varying conditions, suggesting that the simulated control logic closely mirrors actual converter behavior. **Figures 20 and 21** effectively capture the transition from DC to AC stages, confirming proper hardware implementation of the PV charger and inverter. The simulated output in **Figure 22** and its real-world counterpart in **Figure 23** show good waveform consistency and minimal distortion, reinforcing the fidelity of the inverter model and PWM control scheme. **Figure 24**, which tracks the state of charge (SOC) and power losses under droop control, is particularly important for assessing the EMS efficiency—however, this could benefit from more detailed temporal resolution or quantitative annotations. Lastly, **Figure 25** illustrates the holistic microgrid interconnection and supports the testbed's practical applicability. Overall, the close agreement between simulation and experimental data across the figures strengthens the credibility of the proposed EMS and control strategies.

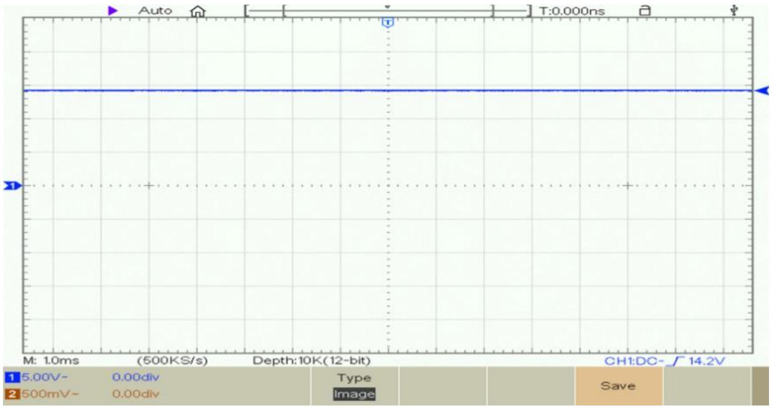

Fig.17. The output of PV Array in practical.

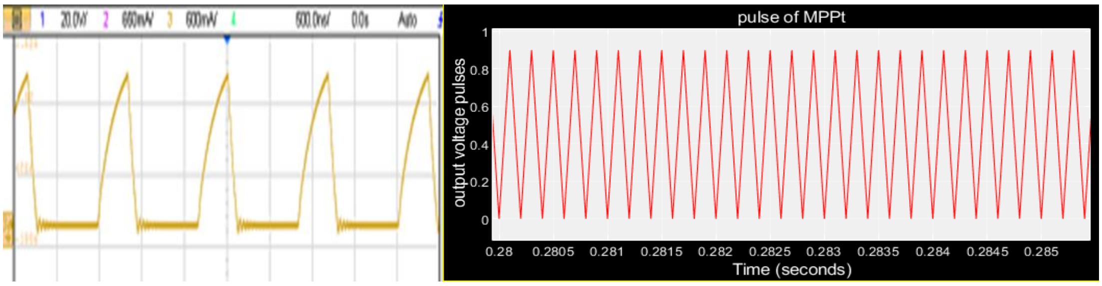

Fig 18. The input of pulse of Buck – Boost converter from Simulation program.

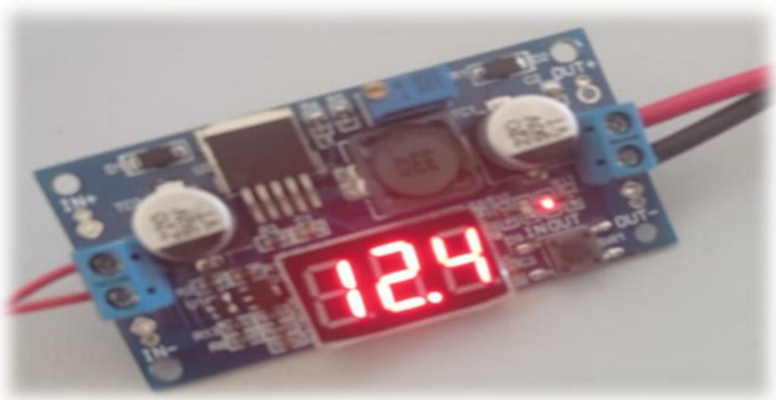

Fig.19. Output voltage From Buck-Boost Converter.

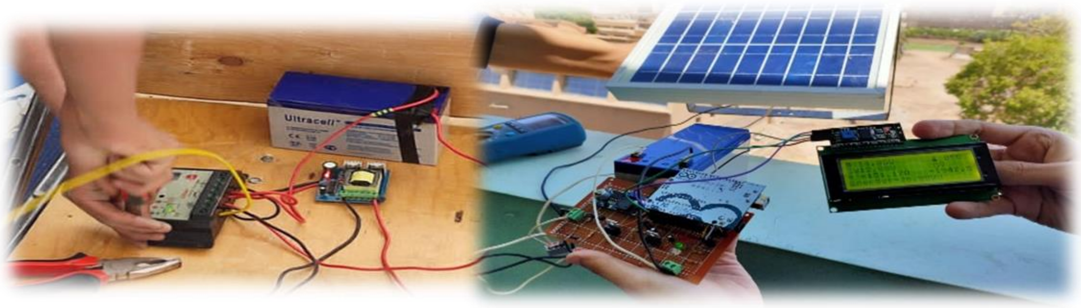

Fig.20. Connection of PV Charger.

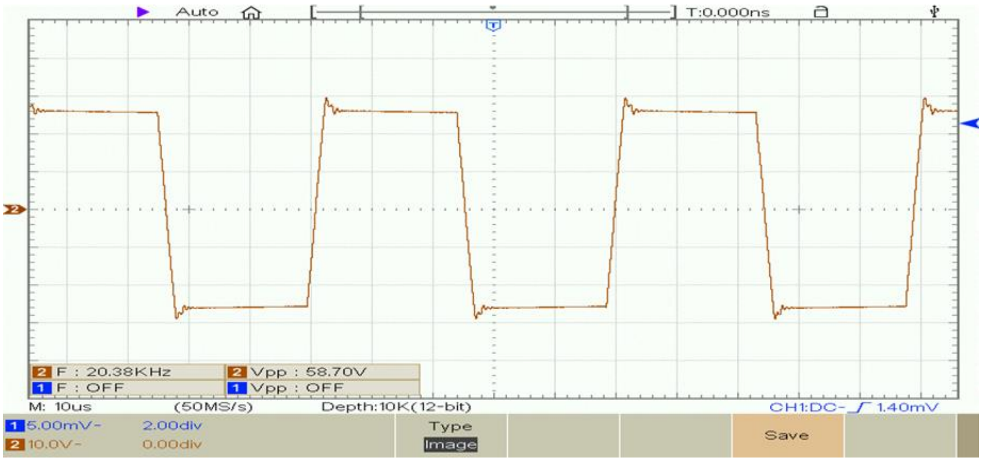

Fig. 21. Output of inverter.

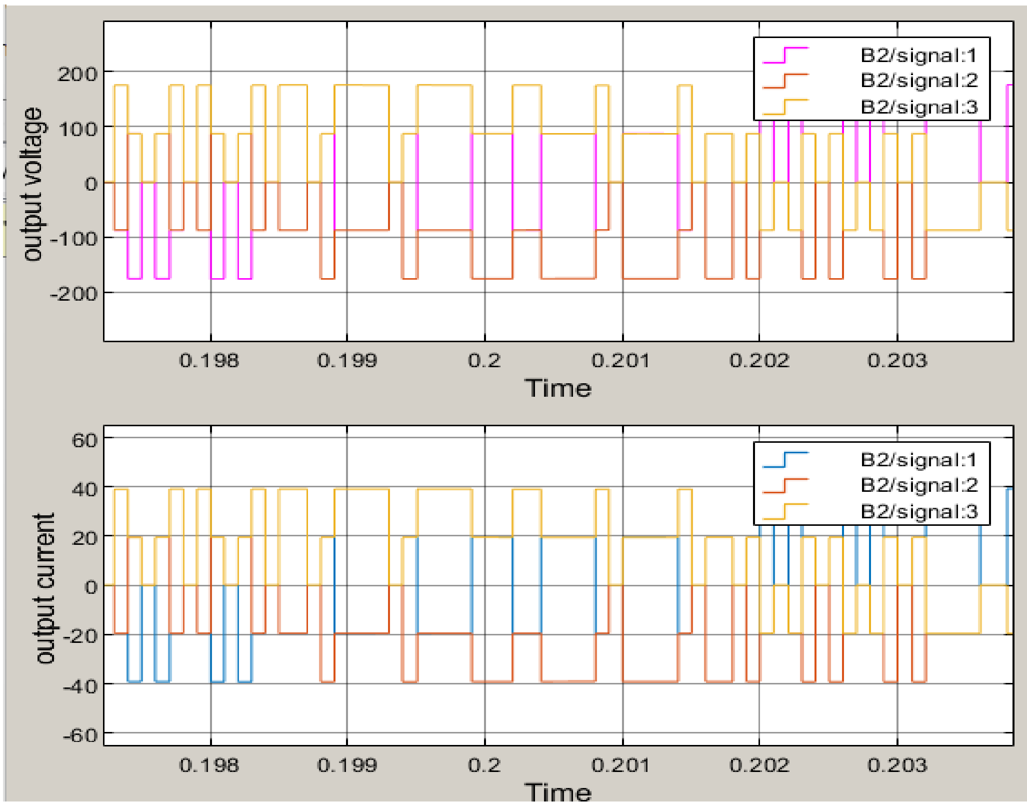

Fig. 22. The output three-phase system from Matlab/Simulation program.

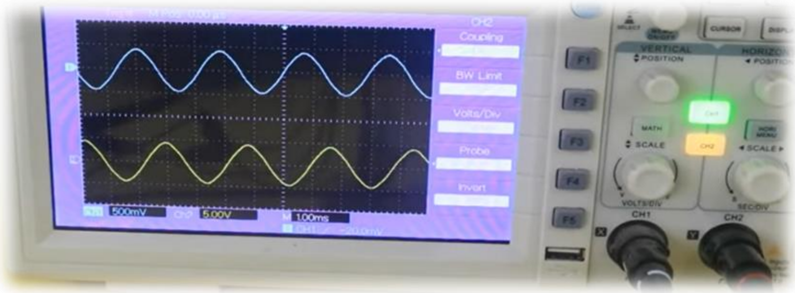

Fig. 23. Output of Inverter (AC Power).

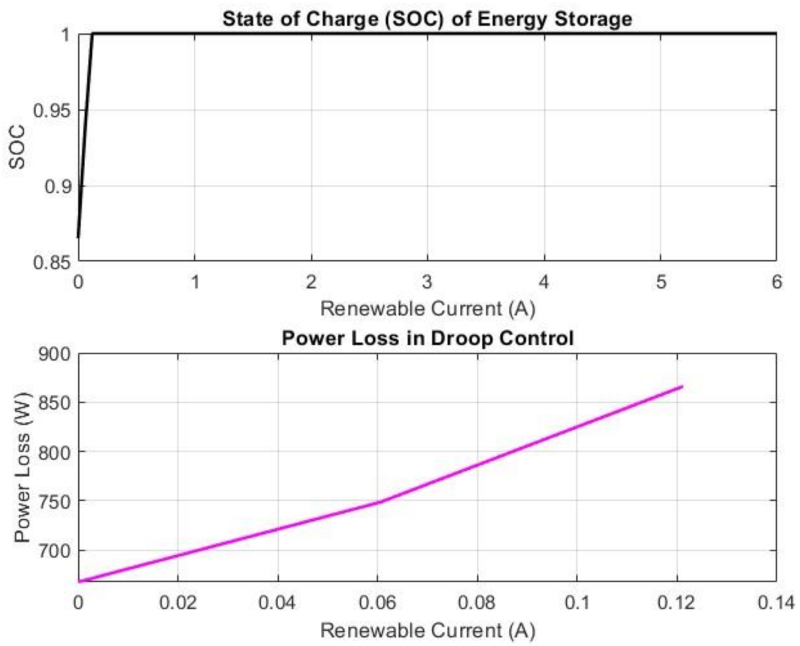

Fig.24. SOC of Energy and power losses in Droop control system

Fig.25. DC Microgrid system connection.

The presented DC microgrid testbed successfully demonstrates the integration and control of renewable energy sources using advanced power electronic interfaces. Simulation and experimental results exhibit strong alignment, confirming the effectiveness of the energy management strategies in achieving reliable power flow control, stable voltage regulation, and efficient current sharing. The use of a DC generator as a wind turbine emulator, while limited in dynamic range, provides a cost-effective and functional means for replicating wind energy input in a controlled lab environment. Overall, the modular design and validated performance of the testbed make it a valuable platform for both research and educational purposes, supporting rapid prototyping and real-time evaluation of microgrid control strategies.

5. CONCLUSION

This research presents a scalable testbed for DC microgrid energy management, integrating distributed renewable energy sources such as photovoltaic (PV) panels and wind turbines with advanced power electronic converters. The suggested system makes good use of adaptive control techniques to improve current sharing, voltage regulation, and system stability in general. The results show that the constructed testbed offers a dependable platform for researching energy storage integration, power flow control, and microgrid operations through laboratory experiments and simulations. The precision and effectiveness of the energy management system (EMS) in place are confirmed by the strong agreement between simulation and experimental results. Rapid prototyping of microgrid control strategies is made possible by the testbed's modularity and versatility, which make it appropriate for both research and instructional uses. Bidirectional converters, PWM inverters, and LC filters work together to provide smooth grid synchronization and high-quality power delivery. Additionally, the adaptive control of the Buck-Boost converter enhances system performance under varying load and generation conditions. Overall, the proposed testbed serves as a valuable tool for exploring distributed renewable energy management solutions, optimizing microgrid performance, and advancing research in sustainable energy systems. Future work will focus on enhancing real-time control algorithms, integrating smart grid functionalities, and expanding the system to accommodate additional renewable sources and load scenarios.

The Future work will focus on expanding smart grid functionalities and incorporating machine learning-based optimization techniques. Overall, DC microgrid provides a versatile platform for researchers and educators to explore and develop distributed energy management solutions for microgrids. The results support the effectiveness of a bidirectional controller on the grid. The microgrid's efficiency fluctuations with the insolation level and state are discussed. We could also take the effect of the harmonic distortions on the microgrid and the AC coupling.

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