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Optimization and Control of Hybrid Renewable Energy Source DC Micro-Grid Via Advance Control Strategies Using Matlab/Simulation

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Abstract: The growing need for sustainable energy solutions has made DC micro-grids a key part of modern power distribution. However, keeping a stable DC bus voltage during unpredictable weather and changing load conditions is still a major challenge. This research presents a new DC micro-grid design that integrates Solar Photovoltaic (PV) and Wind Energy systems. The main innovation in this work is the use of a Zeta Converter as the primary AC-DC interface. This setup provides a non-inverting output and significantly lower current ripples compared to traditional Buck-Boost or SEPIC designs. To deal with the inconsistent nature of renewable energy, a Hybrid Energy Storage System (HESS) combines a Lithium-ion battery bank with an Ultracapacitor. This combination supplies both high energy density and quick responses. Simulation studies done in MATLAB/Simulink confirm that the system can maintain a steady DC link voltage, ensuring smooth power delivery to AC and multi-level DC loads.
Keywords: DC Micro-grid, Renewable Energy, Photovoltaic (PV) System, Wind Energy, Energy Storage System, Zeta converter.

I. INTRODUCTION

The growing need for efficient, reliable, and sustainable energy systems has spurred rapid development in smart grid technologies. In this context, DC smart grids are attracting attention for their ability to integrate renewable energy sources, cut conversion losses, and boost overall system efficiency. A DC micro-grid, which is a vital part of the smart grid, uses intelligent control strategies and modern power electronic interfaces to manage and deliver energy effectively.

The proposed DC micro-grid system connects to a 415 V AC utility source and incorporates renewable energy sources like photovoltaic (PV) and wind energy systems. Alongside traditional sources, it includes energy storage devices such as batteries, ultracapacitors, and electric vehicles (EVs) to improve system reliability, stability, and dynamic response. This hybrid setup allows the micro-grid to deliver high-quality power to both DC and AC loads while optimizing the use of available energy resources.

Despite substantial research on DC micro-grids, many current systems rely on traditional setups and do not effectively integrate renewable energy sources. Also, practical applications of DC micro-grids remain limited, with several studies mainly addressing power quality improvements without fully tackling smart energy management.

To address these challenges, this paper proposes a new DC micro-grid system for smart energy delivery that combines renewable energy sources, various energy storage devices, and electric vehicles. It also analyzes the performance of power electronic converters, conducting a comparative study between conventional Buck converters and Zeta converters. The findings show that the Zeta converter offers better efficiency and power quality.

The rest of this paper is organized as follows: Section II outlines the system configuration, Section III explains the control strategy, Section IV reviews the simulation results, and Section V wraps up the paper.

II. LITERATURE REVIEW

The rapid increase in energy demand and growing environmental concerns have pushed research in renewable energy systems and smart grid technologies. Recently, DC micro-grids have attracted significant attention due to their ability to integrate various energy sources while ensuring efficient, high-quality power delivery. Researchers have been working on developing effective micro-grid designs, hybrid renewable energy systems (HRES), and smart control strategies to improve system performance and reliability.

Liu et al. proposed a DC micro-grid system that connects renewable energy sources and electric vehicles (EVs) for efficient energy delivery.

This system includes several components: AC utility supply, renewable sources like photovoltaic (PV) and wind energy, energy storage devices, and smart control units. This setup allows for efficient energy distribution to both AC and DC loads. The authors noted that DC micro-grid designs enhance power quality by removing harmonic issues often found in AC systems. Additionally, the common DC link simplifies thesystem design and boosts overall efficiency.

Integrating renewable energy sources is a major focus in modern micro-grid systems. Sources like solar and wind energy are environmentally friendly and decrease reliance on fossil fuels, but their unpredictable nature creates challenges for reliable power generation. To tackle this issue, hybrid systems combining PV and wind energy have been thoroughly studied. Due to their complementary traits, where solar energy is available during the day and wind energy is often stronger at night or in varying weather, these systems enhance the overall reliability and continuity of power supply.

Energy storage systems are vital for maintaining stability and reliability in DC micro-grids. Various studies have highlighted the roles of batteries, ultracapacitors, and electric vehicles as storage options. Batteries offer long-term energy storage, while ultracapacitors provide high power density and quick response for temporary conditions. Furthermore, EVs serve as dynamic storage units through bidirectional power flow, enabling vehicle-to-grid (V2G) operation. This combination increases system flexibility and helps meet load demand during peak times or when renewable generation is low.

Another key area of research is developing strategies for smart energy management. DC micro-grids usually operate in different modes, including AC supply mode, renewable energy mode, hybrid mode, and standby mode. These modes control power flow between sources, storage devices, and loads based on what is available and needed. Smart control systems focus on using renewable energy and storing excess energy, leading to better efficiency and less dependence on conventional sources.

Besides DC micro-grids, hybrid renewable energy systems have been widely studied to improve performance and cost-effectiveness. Trape and Hellany explored the design and optimization of hybrid systems that integrate wind turbines, PV systems, and storage units. Their research emphasized the importance of system sizing and design for optimal performance. They used optimization tools like HOMER and IHOGA to evaluate technical and economic factors, allowing for the identification of effective system designs.

A significant challenge in hybrid systems is balancing energy generation with load demand. To address this, the Load Coverage Rate (LCR) concept measures the portion of load demand met by renewable sources. Higher LCR values mean less dependency on the main grid and better system independence. Studies show that adding multiple renewable sources with storage systems greatly improves load coverage and system reliability.Simulation and modeling tools are crucial for analyzing and verifying micro-grid performance before practical use. MATLAB/Simulink is commonly used for modeling renewable energy systems and assessing aspects like voltage stability, power output, and system efficiency. Earlier studies have pointed out challenges such as voltage ripple and stability issues, which can be addressed through better control strategies and power electronic converters.

Overall, the literature reviewed shows that DC micro-grids and hybrid renewable energy systems provide a promising solution for modern power distribution. Incorporating renewable sources, improved storage technologies, and smart control strategies significantly boosts system efficiency, reliability, and sustainability. However, there is still a need for better system configurations, enhanced converter performance, and practical implementation methods. These research gaps drive the development of the proposed DC micro-grid system with advanced converter design and smart energy management.

III. METHODOLOGY

This research focuses on developing and analyzing a multi-source DC micro-grid using MATLAB/Simulink. It includes creating mathematical models, designing the circuit, and validating the system through simulation. The study explains how solar (PV) and wind energy sources are integrated, how a Zeta converter is used for accurate voltage regulation, and how a Battery–Supercapacitor Hybrid Energy Storage System manages power sharing. The main goal is to maintain a stable DC bus even when load conditions change dynamically.

1) PHOTOVOLTAIC SYSTEM

The photovoltaic (PV) system forms a primary renewable energy source in the proposed DC micro-grid architecture. It converts solar energy directly into electrical energy using semiconductor-based solar cells. In this system, the PV array is designed to generate DC power, which is further regulated and conditioned through a DC–DC converter to maintain a stable DC bus voltage. Due to the intermittent nature of solar irradiance, the output of the PV system varies with environmental conditions such as sunlight intensity and temperature. To maximize the energy extraction, a Maximum Power Point Tracking (MPPT) algorithm is employed, ensuring that the PV system operates at its optimal efficiency under varying conditions.

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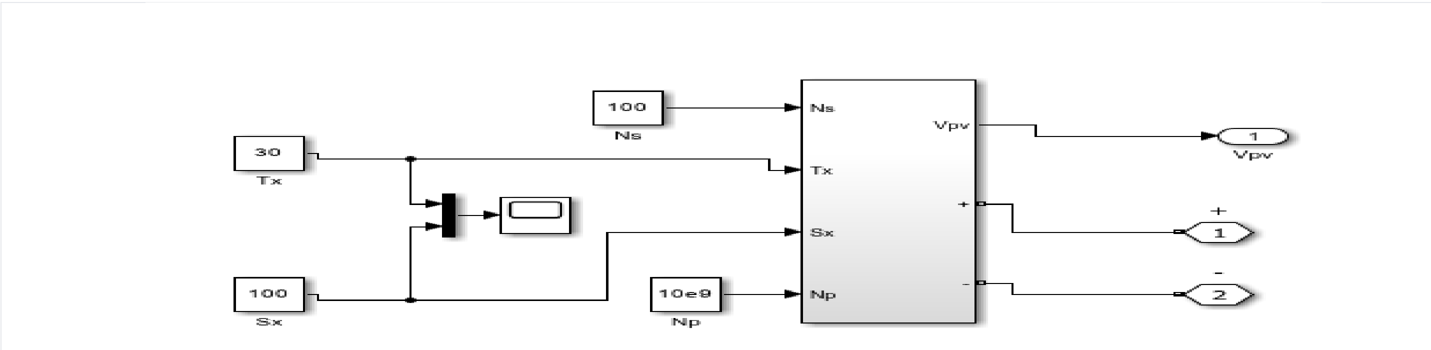
The generated power is either supplied directly to the DC loads or stored in energy storage devices such as batteries and ultracapacitors for later use. Integration of the PV system within the DC micro-grid enhances sustainability, reduces dependency on conventional energy sources, and contributes to improved overall system efficiency and reliability.

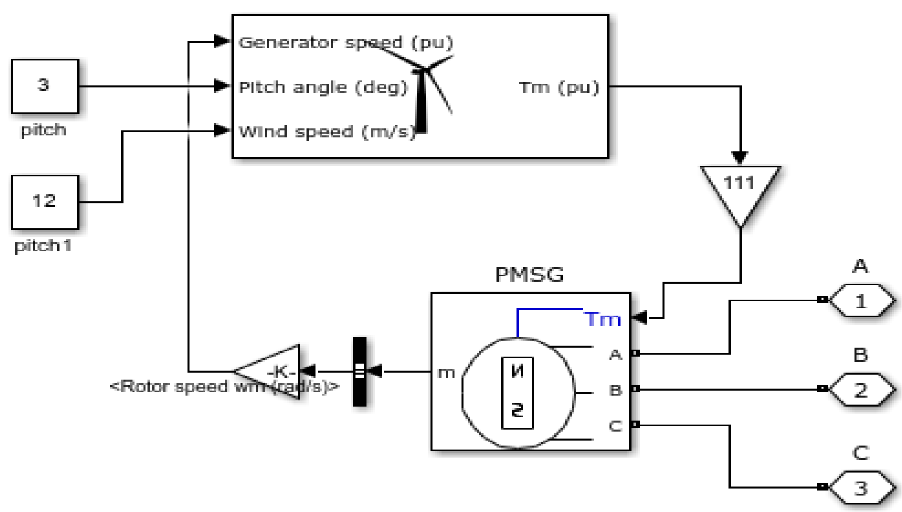


2) WIND SYSTEM

In this project, the wind energy conversion system is model in MATLAB/Simulink to represent a practical wind turbine operation. The turbine takes inputs such as generator speed, pitch angle, and wind speed. In this model, the pitch angle is set to 3° and wind speed is 12 m/s, representing normal operating conditions.

Based on these inputs, the turbine generates mechanical torque (Tm), which is then scaled using a gain block of 111. This torque is applied to a Permanent Magnet Synchronous Generator (PMSG), which converts mechanical energy into three-phase AC output (A, B, C).

The rotor speed is also monitored for control and stability. Overall, this setup shows how wind energy is effectively converted into electrical power and integrated into the hybrid renewable energy system.

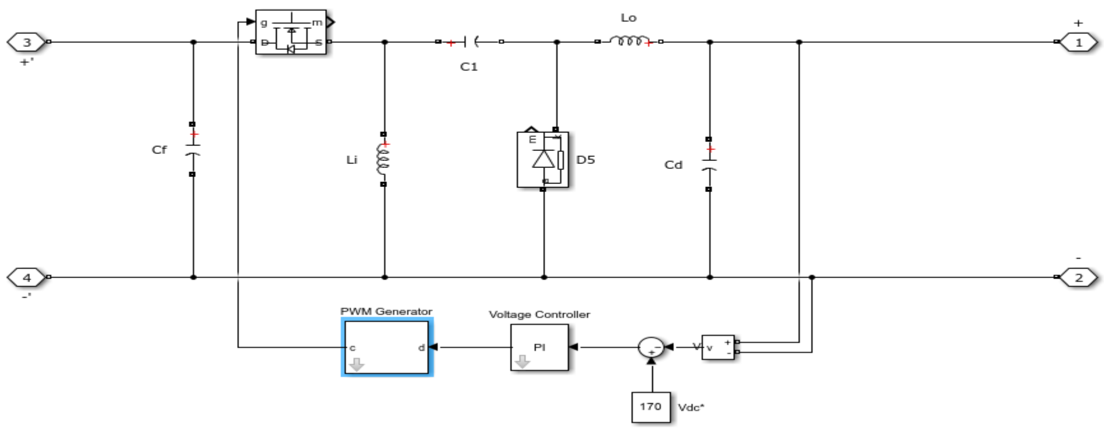


3) ADVANCE POWER CONDITIONING VIA ZETA CONVERTER.

In this project, a Zeta converter is used to interface the 415V AC utility source with the DC micro-grid. It is a fourth-order DC-DC converter consisting of two inductors, two capacitors, and a switch.

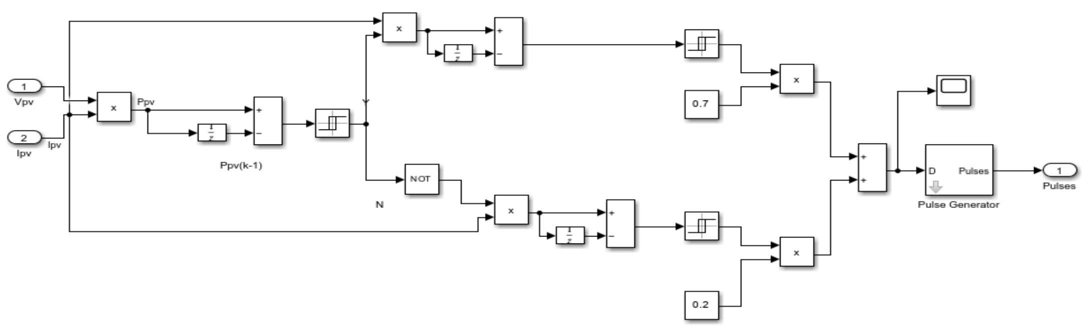
The main advantage of the Zeta converter is that it provides a non-inverted output voltage and maintains continuous output current, which helps in reducing voltage ripples and THD on the 100V–170V DC bus.

By controlling the duty cycle (D), the converter can step up or step down the rectified voltage, ensuring stable output even during grid fluctuations.



4) BUCK BOOST CONVERTER

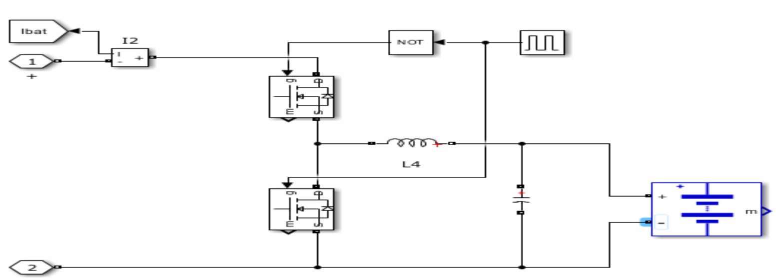
In this project, a Buck Boost converter regulates the output of the PV system and keeps a stable DC voltage. The PV panel generates variable voltage based on solar irradiation, measured as Vpv and Ipv. The system uses a Perturb and Observe (P&O) MPPT algorithm. This algorithm takes Vpv and Ipv as inputs and creates switching pulses. These pulses control the switching device (MOSFET/IGBT) of the Buck Boost converter to extract maximum power from the PV panel. The converter has key components such as an inductor (L1), resistor (R1), diode, switch, andcapacitor. By adjusting the duty cycle (D), the converter can operate in both buck mode (step-down) and boost mode (step-up), depending on the load requirement. When D is less than 0.5, it works in buck mode. When D is more than 0.5, it works in boost mode. The output current (I1) is measured to ensure proper power delivery. This setupmaintains a stable and optimized DC output, making it suitable for integration into the hybrid renewableenergy system.



5) HYBRID ENERGY STORAGE SYSTEM.

a) BATTERY STORAGE SYSTEM

In this system, a battery is used to store excess energy and supply power when needed. A bidirectional DC-DC converter (with two switches and inductor L4) controls charging and discharging.Charging: Stores energy when supply is highDischarging: Supplies power when demand increasesThe battery current (Ibat) is monitored, and complementary switching ensures proper operation.
This unit helps in maintaining stable and reliable in micro-grid.



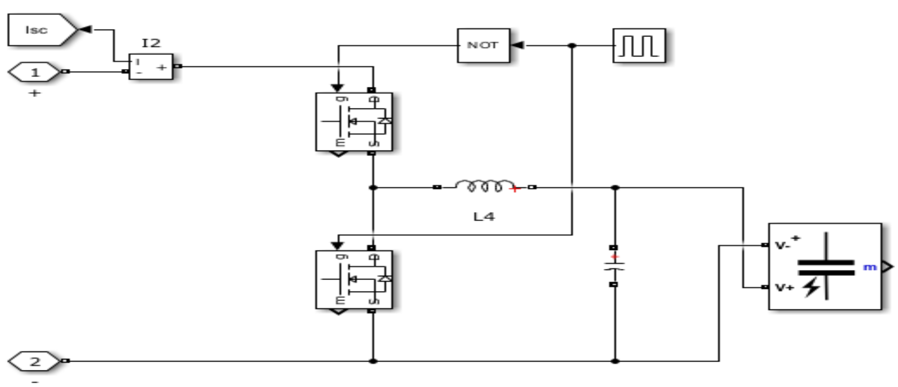
b) SUPER CAPACITOR

In this system, a supercapacitor is used to provide quick energy support during sudden changes in load. It works together with the battery to improve overall system performance.The setup uses a bidirectional converter with two switches, an inductor (L4), and PWM control. The current (Isc) is monitored to manage its operation.

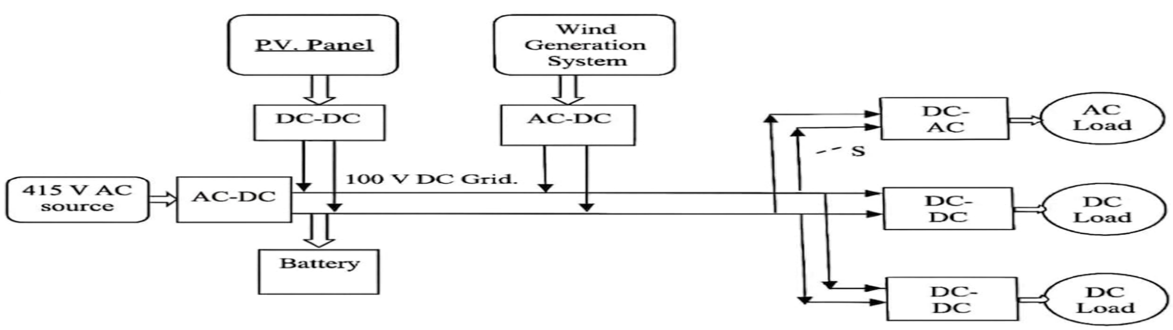
Charging: Stores extra energy when available

Discharging: Quickly supplies power during sudden demand

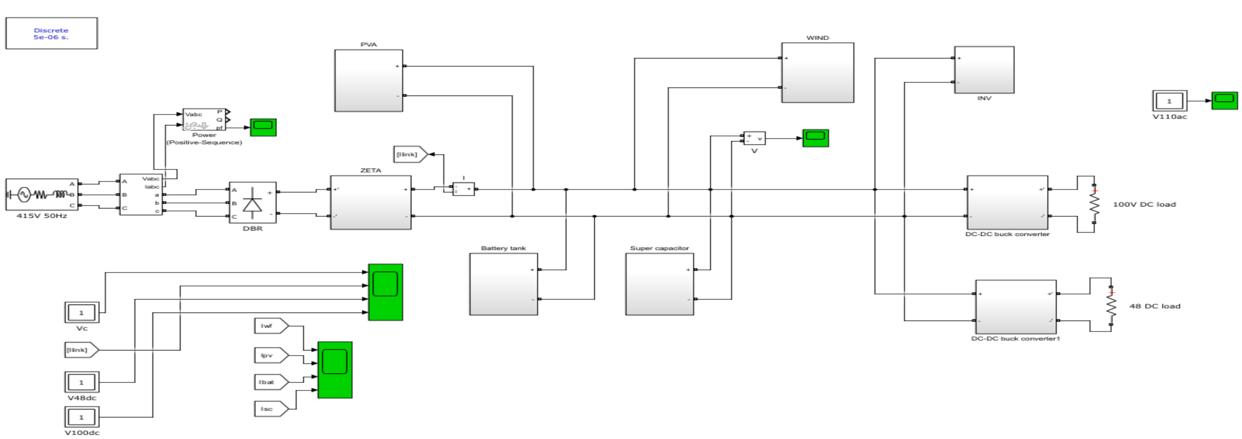
Due to its fast response, the supercapacitor helps in reducing voltage fluctuations and keeps the DC bus stable.



IV. BLOCK DIAGRAM



V. FINAL SIMULATION



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The proposed DC micro-grid system is model and simulated in MATLAB/Simulink. A 415 V AC source is converted to DC using a rectifier to form a common DC bus, which integrates renewable sources such as PV and wind systems along with battery storage. The system supplies power to DC loads through controlled DC–DC converters.

A comparative analysis between Buck and Zeta converters is performed. The results show that the system maintains stable DC bus voltage and ensures reliable power delivery under varying conditions. The Zeta converter demonstrates better performance in terms of voltage regulation, reduced ripple, and improved efficiency compared to the conventional Buck converter.

Overall, the simulation validates the effectiveness of the proposed DC micro-grid system for efficient and high-quality power distribution.

VI. CALCULATION

✅ 1. Key Input Parameters

Parameter	Value
Input Voltage (Vin)	54.7 V (max)
Input Current (Iin)	5.58 A (max)
Output Voltage (Vout)	27 V – 100 V
Power (Pout)	~300 W (approx)
Switching Frequency (fs)	50 kHz (typical)

✅ 2. Output Load Resistance (R)

We choose max output power ≈ 300 W for design.

- At Vout = 100 V:

$$I_{out} = \frac{P_{out}}{V_{out}} = \frac{300}{100} = 3\ A$$

$$R = \frac{V_{out}}{I_{out}} = \frac{100}{3} \approx 33.3\ \Omega$$

🔶 For simplicity, use a fixed R = 33.3Ω.

✅ 3. Duty Cycle (D) — Buck-Boost Mode (Non-Inverting)

The output-to-input voltage relationship for **non-inverting buck-boost:**

$$\frac{V_{out}}{V_{in}} = \frac{D}{1-D} \Rightarrow D = \frac{V_{out}}{V_{in} + V_{out}}$$

Let's check limits:

- For Vout = 27V:

$$D = \frac{27}{54.7 + 27} \approx 0.33$$

- For Vout = 100V:

$$D = \frac{100}{54.7 + 100} \approx 0.65$$

So D **ranges from 0.33 to 0.65.**

✅ 4. Inductor (L) Calculation

$$L = \frac{V_{in} \cdot D}{f_s \cdot \Delta I_L}$$

Assume:

- ΔIL = 20% of Iin_max = 0.2 × 5.58 = 1.12 A
- fs = 50 kHz, Vin = 54.7 V, D = 0.5 (midpoint)

$$L = \frac{54.7 \times 0.5}{50 \times 10^3 \times 1.12} \approx 0.488\ mH$$

📌 Use **L = 470 μH or 500 μH** standard value.

✅ 5. Output Capacitor (C) Calculation

$$C = \frac{I_{out} \cdot D}{\Delta V_{out} \cdot f_s}$$

Assume:

- ΔVout = 1% of 100V = 1V
- D = 0.65, Iout = 3A

$$C = \frac{3 \times 0.65}{1 \times 50,000} = 39\ \mu F$$

📌 Use C = 47 μF or 68 μF (low ESR electrolytic or ceramic).

✅ 6. Input Filter Capacitor (Cin)

$$C_{in} = \frac{I_{in} \cdot D}{\Delta V_{in} \cdot f_s}$$

Assume ΔVin = 1V ripple:

$$C_{in} = \frac{5.58 \cdot 0.65}{1 \cdot 50,000} \approx 72.5\ \mu F$$

📌 Use **Cin = 100 µF** electrolytic or ceramic.

✅ 7. PI Controller Tuning (Trial Method)

Start with:

- **Proportional gain (Kp)** = 0.5
- **Integral gain (Ki)** = 50

Then tune as per output response:

- Increase **Kp** for faster rise time
- Increase **Ki** to eliminate steady-state error

VII. RESULT

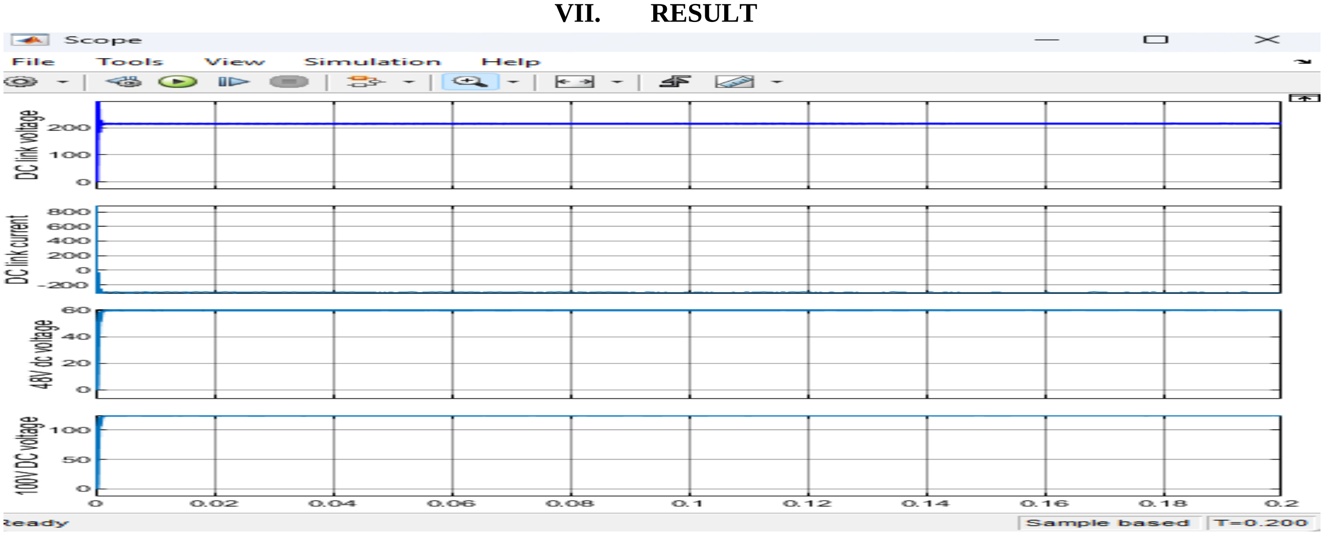

Fig.LOAD AND GRID

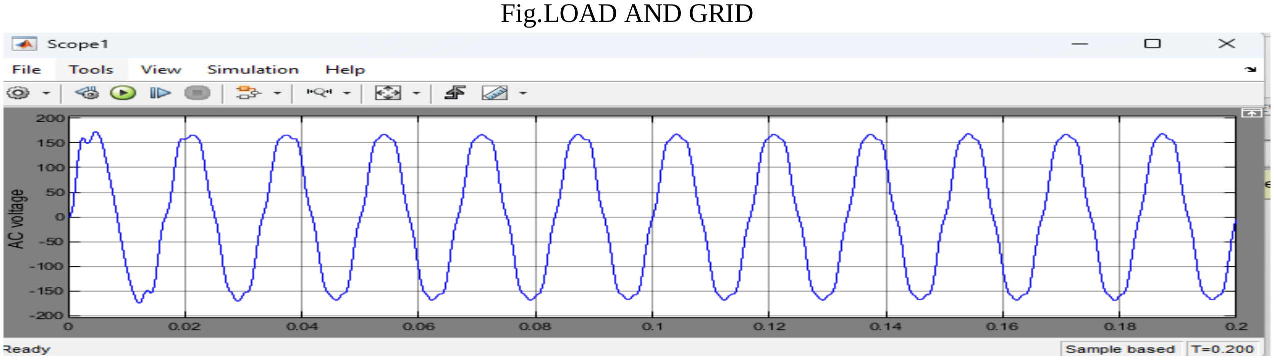

Fig. AC Voltage

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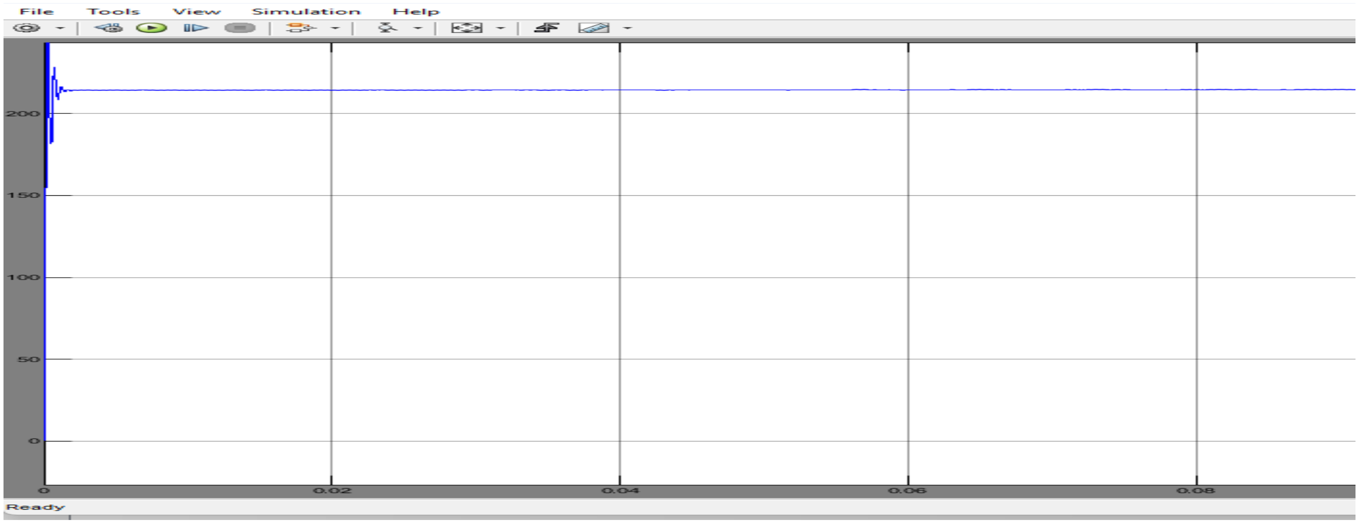

Fig. Grid voltage

In this study, we successfully brought the proposed DC micro-grid system to life using MATLAB/Simulink. By integrating solar PV, wind energy, a battery bank, and a supercapacitor, the system seamlessly converts a standard 415V AC input into a highly stable DC output.

Our simulation results clearly highlight the system's reliability, as we managed to keep the main DC bus voltage rock-solid at around 170V. From this stable backbone, the micro-grid effortlessly powers a variety of load requirements, delivering precise outputs of 110V AC, 100V DC, and 48V DC.

The real game-changer in this setup is the teamwork between the battery and the supercapacitor. While the battery acts as the dependable, long-term energy provider, the supercapacitor steps in as a quick-response buffer, instantly absorbing sudden load spikes and minimizing voltage drops. Ultimately, our findings prove that this hybrid micro-grid delivers incredibly stable and reliable energy, ensuring smooth power sharing no matter how unpredictable the load or weather conditions get.

VIII. CONCLUSION

The proposed DC micro-grid system has been designed and simulated by combining multiple energy sources such as solar photovoltaic (PV), wind energy, and the utility grid. It also includes power electronic converters and energy storage systems to improve performance, flexibility, and reliability. Components like the Zeta converter, Buck-Boost converter, and bidirectional DC-DC converters are crucial for efficient power management and voltage regulation.

The system can maintain a stable DC bus voltage of about 170V, even with changing load and source conditions. This stable DC link ensures proper power distribution to various types of loads. The system successfully provides 110V AC through an inverter for household applications. It also delivers regulated 100V DC and 48V DC outputs using buck converters for DC loads. This multi-level power distribution shows the versatility of the proposed micro-grid.The Zeta converter, used to connect to the utility grid, offers advantages like non-inverted output voltage, continuous current, and reduced ripple content. This leads to better power quality and lower Total Harmonic Distortion (THD). The Buck-Boost converter paired with the PV system ensures maximum power extraction through MPPT (Perturb and Observe algorithm), improving the efficiency of solar energy use.A key feature of this system is its hybrid energy storage system, which includes both a battery and a supercapacitor. The battery handles long-term energy storage and backup, while the supercapacitor responds quickly to sudden load changes and transient conditions. This combination greatly improves system stability, reduces voltage fluctuations, and ensures uninterrupted power supply.

The simulation results show smooth power flow, effective load sharing among different energy sources, and minimal voltage variations. The system operates reliably during changes in renewable generation and load demand, demonstrating the effectiveness of the control strategy.In conclusion, the proposed DC micro-grid system provides a reliable, efficient, and scalable solution for modern energy needs. It is suitable for smart grids, renewable energy integration, and sustainable power systems. It offers improved performance, better power quality, and enhanced operational stability.

The proposed DC micro-grid system effectively integrates multiple energy sources, including AC utility supply, renewable energy (PV and wind), energy storage systems, and electric vehicle support.

The system operates under different modes such as AC mode, renewable mode, hybrid mode, and standby mode, ensuring uninterrupted power supply under various conditions.The DC link voltage is maintained at a stable level, ensuring efficient power sharing and minimizing power quality issues. The system successfully supplies both AC and DC loads, highlighting its flexibility and reducing conversion losses. Simulation results demonstrate smooth power flow, minimal voltage fluctuations, and effective load management.

Overall, the proposed system provides a reliable, efficient, and sustainable solution for modern smart grid applications, validating its suitability for future energy systems.

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