JOURNAL OF MECHANICS OF CONTINUA AND MATHEMATICAL SCIENCES
www.journalimcms.org

ISSN (Online) : 2454 -7190 Vol.-19, No.-10, October (2024) pp 44 - 66 ISSN (Print) 0973-8975

ENERGY MANAGEMENT IN HYBRID PV-WIND-BATTERY STORAGE-BASED MICROGRID USING DROOP CONTROL TECHNIQUE

Bibhu Prasad Ganthia[1], Praveen B. M.[2], Subash Ranjan Kabat[3]
Bijaya Kumar Mohapatra[4], Rabinarayan Sethi[5], Abdulrajak Buradi[6]

[1, 2] College of Engineering and Technology, Srinivas University, Mangalore India.

[3] Department of Electrical Engineering, Radhakrishna Institute of Technology and Engineering, Bhubaneswar, Odisha, India.

[4] Department of Electrical & Electronics Engineering, Einstein Academy of Technology and Management, Bhubaneswar, Odisha, India.

[5]Department of Mechanical Engineering, IGIT, Sarang, Dhenkanal, Odisha, India.

[6]Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Bangalore, Karnataka, India.

Email: [1] jb.bibhu@gmail.com, [2] bm.praveen@yahoo.co.in
[3] subashkabat198@gmail.com, [4] bijaya87@gmail.com
[5] rabinsethi@gmail.com, [6] arbnitk@gmail.com

Corresponding Author: **Bibhu Prasad Ganthia**

https://doi.org/10.26782/jmcms.2024.10.00004

(Received: July 12, 2024; Revised: September 09, 2024; Accepted: September 23, 2024)

Abstract

The paper presents an efficient energy management system designed for a small-scale hybrid microgrid incorporating wind, solar, and battery-based energy generation systems using the droop control technique. The heart of the proposed system is the energy management system, which is responsible for maintaining power balance within the microgrid. The EMS continuously monitors variations in renewable energy generation and load demand and adjusts the operation of the energy conversion systems and battery storage to ensure optimal performance and reliability. The primary objective of the energy management system is to maintain power balance within the microgrid, even in the face of fluctuations in renewable energy generation and load demand. This involves dynamically adjusting the operation of the renewable energy sources and battery storage system to match the instantaneous power requirements of the microgrid. Overall, the paper presents a comprehensive approach to designing and implementing an efficient energy management system for a small-scale hybrid wind-solar-battery-based microgrid to extract maximum profit from electricity generation. By integrating renewable energy sources with energy storage and advanced control algorithms, the proposed system *aims to enhance the reliability, stability, and sustainability of the microgrid's power supply.*

Keywords: Battery Storage, Droop Control, Energy Management System, Microgrids, Optimization, Photovoltaic (PV), Uncertainties, Wind Energy.

I. Introduction

A microgrid is an interconnected system comprising loads and distributed energy resources that can function as a unified entity connected to the utility grid, as illustrated in Figure 1. It has the flexibility to operate in both grid-tied and islanded modes. Within a microgrid, power converters play a critical role in integrating renewable energy sources into the conventional power system through a two-stage conversion process [I]. The DC/DC boost converter connects DC sources such as solar PV and batteries to a common DC bus, while the grid-side inverter converts DC to AC for grid integration. The wind system is connected directly to the AC bus via rotor-side and grid-side converters that are linked to the DC bus. Energy storage systems like batteries are interfaced with the DC bus using bidirectional converters. Modeling and simulation of the microgrid system can analyze electromagnetic transients, dynamic, and steady-state behaviors simultaneously [II]. The development of power electronic converters and control algorithms is essential for power smoothing during microgrid integration. Controller hardware-in-the-loop testing, which involves the physical controller interacting with a microgrid model and associated power devices, is used to ensure stability. Microgrids offer a form of localized energy generation, producing electricity for nearby consumers, and distinguishing them from large centralized grids that have traditionally supplied most of our electricity [III]. Centralized grids deliver power from distant power plants through transmission and distribution lines, but this long-distance transfer results in inefficiencies, with up to 8% to 15% of electricity dissipating during transit [IV]. A microgrid mitigates this issue by generating power close to the point of consumption, such as within buildings or, in the case of solar panels, on rooftops. Additionally, a microgrid can disconnect from the central grid and operate autonomously. This islanding feature enables it to continue supplying power to its customers even during disruptions or outages on the main grid caused by storms or other events [V].

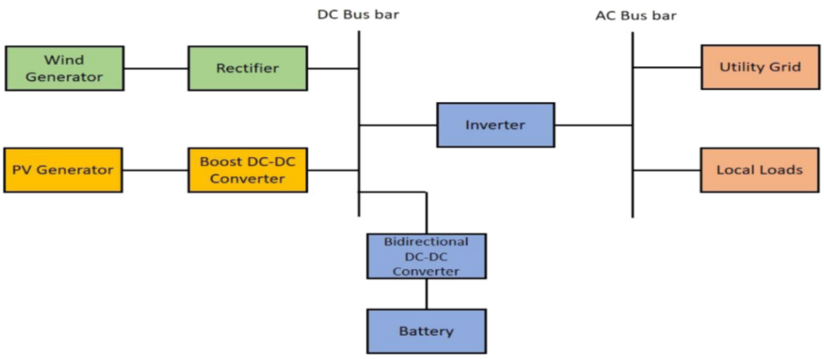


Fig. 1. Microgrid model

In the United States, the central grid is particularly vulnerable to outages due to its vast size and extensive interconnected network, which includes more than 5.7 million miles of transmission and distribution lines. The fragility of this system became evident during the Northeast Blackout of 2003, where a single tree falling on a power line resulted in a widespread power outage affecting multiple states and even crossing international borders into Canada. Microgrids, through their ability to operate in island mode, can avoid such cascading failures. Although microgrids can run independently, they generally remain connected to the central grid, except in remote areas where access to the central grid is limited or unreliable. In normal conditions, microgrids and the central grid operate in a symbiotic manner, as described below [VI]. Furthermore, modern microgrids, especially advanced systems, are highly intelligent. This intelligence is derived from a microgrid controller, which acts as the central brain of the system. The controller manages generators, batteries, and nearby building energy systems with great precision and sophistication. It coordinates multiple resources to achieve the energy objectives set by the microgrid's customers, such as minimizing costs, maximizing clean energy usage, or enhancing electric reliability. The controller optimizes resource utilization by increasing or decreasing the contribution of various microgrid assets, much like a conductor directing musicians to adjust their performance to achieve the desired outcome [VII].

II. Photovoltaic Model

A Photovoltaic (PV) system is a technology that converts sunlight directly into electricity using semiconductor materials, typically organized into solar cells and modules. The single-diode model is a simplified mathematical representation of a PV cell's electrical behavior, using an equivalent circuit that includes a current source, a diode, a series resistor, and a parallel resistor. The current source simulates the photocurrent generated by sunlight, while the diode accounts for the cell's inherent non-linear behavior. The resistors represent internal losses due to resistance within the cell and leakage currents. This model is widely used for analyzing and optimizing PV cell performance due to its simplicity and ability to accurately predict the cell's output characteristics under different conditions. The photovoltaic model is shown below in figure no. 2.

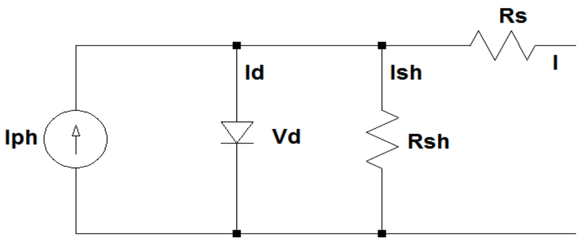


Fig. 2. Single diode model

The single-diode model of a solar cell is represented by an equivalent circuit that includes one current source, one diode, and two resistors. The current source in the circuit simulates the photocurrent generated when sunlight hits the cell, while the diode models the inherent non-linear behavior of the PV cell. The two resistors, a series resistor (Rs) and a parallel or shunt resistor (Rsh), represent internal losses: Rs accounts for resistive losses within the cell and connections, while Rsh captures leakage currents across the cell. This model is widely used because it offers a good balance between simplicity and accuracy for predicting the electrical characteristics of the PV cell [IX].

$$I = I_{lg} - Ios\left[\exp\left\{q \times \frac{V+I\times Rs}{A\times K\times T}\right\} - 1\right] - \frac{V+I\times Rs}{Rsh} \tag{1}$$

Where,

$$Ios = Ior \times \left(\frac{T}{Tr}\right)^3 \times \left[\exp\left\{q \times Ego \times \frac{\frac{1}{Tr}-\frac{1}{T}}{A\times K}\right\}\right] \tag{2}$$

$$I_{lg} = \{I_{scr} + K_i \times (T-25)\}\times lambda \tag{3}$$

The characteristic equation depends upon the connection of the solar module. That is the total no. of cells connected in series and parallel. Current variation in the solar module due to shunt resistance is less and due to the series resistance is more [X].

$$I = Np + Ilg \times Ios \times \left[\exp\left\{q \times \frac{\frac{V}{Ns}+I\times\frac{Rs}{Np}}{A\times K\times T}\right\} - 1\right] - \frac{V\times\frac{Np}{Ns}+I\times Rs}{Rsh} \tag{4}$$

From this, it was observed that the cell works as constant CS for small operating voltages. It also works as constant VS for a small operating current. When the photon of light drops on a solar cell, it delivers the free electrons from the upper layer of the cell. By applying the formula of threshold energy, we can get the appropriate intensity of light [XI].

III. Wind Turbine Model

A Wind Energy Conversion System (WECS) is a technology used to convert wind energy into electrical energy shown below in figure no. 3. It typically consists of several components working together to harness the power of the wind and produce electricity. Aerodynamically designed blades mounted on a rotor hub. Rotor blades capture the kinetic energy of the wind and convert it into rotational mechanical energy. The rotor hub is the central component to which the rotor blades are attached. It transfers the rotational energy from the blades to the rotor shaft. A long, sturdy rotor shaft is connected to the rotor hub [XII]. As the rotor blades rotate, they transfer mechanical energy to the rotor shaft. In some designs, a gearbox may be included to increase the rotational speed of the rotor shaft, optimizing it for the generator's requirements. The generator converts the mechanical energy from the rotor shaft into electrical energy. Different types of generators can be used, including synchronous, asynchronous, and doubly-fed induction generators (DFIG). Yaw mechanism that rotates the entire turbine nacelle to align the rotor blades with the direction of the wind. This ensures optimal energy capture. The tower provides support for the entire wind turbine structure, raising it to an optimal height above the ground to capture higher wind speeds [XIII]. The control system monitors various parameters such as wind speed, rotor speed, power output, and grid conditions. It adjusts the pitch angle of the blades, controls the yaw mechanism, and manages the electrical output of the generator to optimize energy production and ensure safe operation. In grid-connected systems, the electrical energy generated by the wind turbine is converted to a form suitable for grid integration. This may involve power electronics such as inverters or rectifiers. The foundation provides stability and support for the entire wind turbine structure, anchoring it securely to the ground or seabed [XIV].

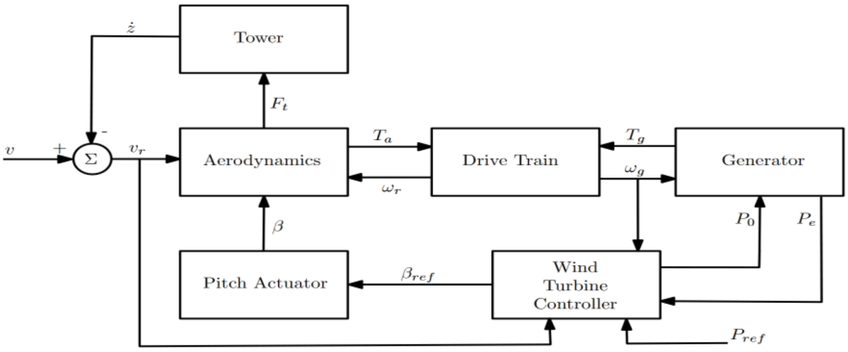


Fig. 3. Wind Energy Conversion System

A Wind Energy Conversion System is shown in figure no. 3 is a complex engineering system that harnesses the natural power of the wind to produce clean, renewable electricity. It plays a crucial role in the transition to a more sustainable energy future. A Doubly-Fed Induction Generator (DFIG) is a type of wind turbine generator that uses a wound rotor induction generator system. The rotor assembly consists of the rotor shaft and the rotor windings [XV]. The rotor windings are connected to the grid via slip rings and brushes, allowing for bidirectional power flow between the rotor and the grid. The stator assembly consists of the stator windings, which are fixed and typically connected directly to the grid. When the rotor is excited with a three-phase AC current, it induces a rotating magnetic field in the stator windings, which generates electrical power. The converter system is a crucial component of the DFIG. It consists of two power converters: the rotor-side converter (RSC) and the grid-side converter (GSC). The RSC controls the rotor current and allows for variable speed operation of the turbine, while the GSC controls the power flow between the stator and the grid [XVI]. The pitch control system is responsible for adjusting the pitch angle of the turbine blades to optimize power production and protect the turbine during high wind speeds. It typically consists of hydraulic or electric actuators that adjust the angle of the blades based on input from sensors monitoring wind speed and turbine performance. The yaw control system is responsible for orienting the turbine rotor into the wind to maximize power production. It typically consists of yaw motors and controllers that adjust the orientation of the entire turbine nacelle in response to changes in wind direction [XVII]. The control system of a DFIG-based wind turbine is responsible for monitoring various parameters such as wind speed, rotor speed, grid voltage, and grid frequency. It uses this information to regulate the operation of the turbine, including the pitch angle of the blades and the power output of the converters, to optimize energy production and ensure stable grid integration. This model outlines the key components and systems of a DFIG-based wind turbine, highlighting its ability to achieve variable speed operation and provide grid support through power electronics control. Using the fixed blade angle method, the angle of the turbine blades is fixed. This means that the blades cannot adjust their orientation to the wind. As a result, the turbine operates optimally at a specific wind speed range, and beyond that range, the fixed blades act as a natural speed limiter, preventing the turbine from spinning too fast and potentially causing damage. Active stall control involves intentionally stalling the turbine blades by adjusting their angle during high wind speeds. By changing the angle of attack of the blades, the lift force generated by the wind is reduced, effectively limiting the turbine's power output. Active stall systems typically include mechanisms to adjust the blade angle dynamically in response to changes in wind speed. Pitch control involves adjusting the angle of the turbine blades in real time to optimize their efficiency and control the turbine's power output. When wind speeds exceed a certain threshold, the pitch angle of the blades is adjusted to reduce their surface area exposed to the wind, thereby limiting the amount of power generated by the turbine. Pitch control systems use sensors to monitor wind conditions and adjust the blade angle accordingly [XVIII]. These methods are essential for ensuring the safe and efficient operation of wind turbines across a wide range of wind speeds. By controlling the power output of the turbine, they help to maximize energy production while minimizing the risk of damage to the turbine components. Each method has its advantages and is suitable for different turbine designs and operating conditions. Standalone systems are designed to operate independently of the electrical grid. They are commonly used in remote areas where grid connection is not available or feasible. Since standalone systems don't have the grid as a backup, they often incorporate energy storage solutions such as batteries or pumped hydro storage to store excess energy generated during periods of high wind for use during periods of low wind. Standalone systems must be carefully sized to match the energy demand of the connected loads. Energy management and load-shedding strategies may be employed to ensure that energy supply meets demand. Standalone systems require sophisticated control systems to manage energy production, storage, and distribution efficiently. These systems must adapt to varying wind conditions and load demands to ensure a reliable power supply. Grid-integrated systems are connected to the electrical grid, allowing them to export surplus energy to the grid and import energy when needed. They are commonly deployed in areas with existing grid infrastructure. Grid-integrated systems can provide ancillary services to the grid, such as frequency regulation and voltage support. This helps enhance grid stability and reliability. In many jurisdictions, grid-integrated systems can take advantage of net metering policies, allowing them to offset their electricity bills by exporting excess energy to the grid. Grid-integrated systems must comply with local grid codes and standards to ensure safe and reliable operation. This may involve implementing grid-connection protection systems and meeting specific requirements for voltage and frequency regulation [XIX]. Both standalone and grid-integrated wind energy conversion systems play important roles in the transition to renewable energy. Standalone systems provide energy access in remote areas, while grid-integrated systems contribute to grid stability and help decarbonize the electricity sector. The choice between the two depends on factors such as location, energy demand, grid availability, and regulatory framework.

IV. Battery Storage System

Battery storage systems play a crucial role in microgrids, enhancing their flexibility, resilience, and efficiency. Battery storage systems store excess energy generated by renewable sources, such as solar panels and wind turbines, during periods of low demand or high generation. This stored energy can then be discharged when demand exceeds generation, ensuring a stable and reliable power supply within the microgrid. Battery storage systems allow for load shifting by storing surplus energy during off-peak periods and discharging it during peak demand times. This helps to reduce electricity costs by avoiding expensive peak-hour rates and optimizing energy usage within the microgrid. In grid-connected microgrids, battery storage systems can provide ancillary services to the central grid, such as frequency regulation, voltage support, and grid stabilization. By injecting or absorbing power as needed, battery systems help to maintain grid stability and reliability. Battery storage systems enable microgrids to operate independently from the central grid during outages or emergencies. In islanded mode, batteries serve as a backup power source, ensuring uninterrupted electricity supply to critical loads within the microgrid. It facilitates the integration of variable renewable energy sources, such as solar and wind, into the microgrid. By smoothing out fluctuations in generation and providing firming capacity, batteries help stabilize the grid and maximize the utilization of renewable energy resources. It can be used for peak shaving, reducing peak demand charges by discharging stored energy during periods of high electricity consumption [XX]. This can result in significant cost savings for microgrid operators and end-users. They integrated into the microgrid's control and optimization algorithms, allowing for dynamic management of energy flows and resources. Advanced control strategies optimize battery operation based on factors such as electricity prices, demand patterns, and renewable energy availability. Overall, battery storage systems are essential components of microgrids, enabling them to efficiently manage energy supply and demand, enhance grid stability, and support the integration of renewable energy sources. As battery technology continues to advance, the role of energy storage in microgrids is expected to grow, further contributing to the transition towards a more sustainable and resilient energy system. The battery energy storage systems (BESS) are crucial components in managing the power balance within microgrids, especially when integrating variable renewable energy sources like solar and wind. These systems store excess energy during times of surplus generation and discharge it when demand exceeds supply, helping to stabilize the grid and ensure a reliable power supply. NiCd batteries are known for their durability and reliability. They have a long cycle life and perform well in extreme temperatures. However, they are less energy-dense compared to other battery types and have environmental concerns due to their cadmium content. NiMH batteries offer higher energy density and improved environmental friendliness compared to NiCd batteries. They have a good cycle life and are commonly used in consumer electronics and hybrid electric vehicles. Lead acid batteries are one of the oldest and most established battery technologies. They are cost-effective and have a relatively long cycle life. However, they are bulky, heavy, and have lower energy density compared to other battery types. Li-ion batteries are widely used in BESS due to their high energy density, efficiency, and relatively long cycle life. They are lightweight and have a fast charge/discharge rate, making them suitable for various applications, including grid-scale energy storage. Li-poly batteries are a type of Li-ion battery with a polymer electrolyte. They offer similar advantages to Li-ion batteries, including high energy density and lightweight design. However, they are less common in large-scale energy storage applications. Sodium sulphur batteries operate at high temperatures and are suitable for grid-scale energy storage applications. They have high energy density and long cycle life but require careful thermal management. Sodium nickel chloride batteries, also known as Zebra batteries, operate at high temperatures and offer high energy density and long cycle life. They are used in grid-scale energy storage and electric vehicle applications. Zinc-air batteries utilize zinc and oxygen from the air as reactants, making them lightweight and cost-effective. They have potential for grid-scale energy storage but are still in the early stages of commercialization. Each battery type has its advantages and disadvantages, and the choice depends on factors such as cost, energy density, cycle life, operating conditions, and specific application requirements. As technology advances and economies of scale improve battery energy storage systems are expected to play an increasingly important role in enabling the transition to a more sustainable and resilient energy system [XXI].

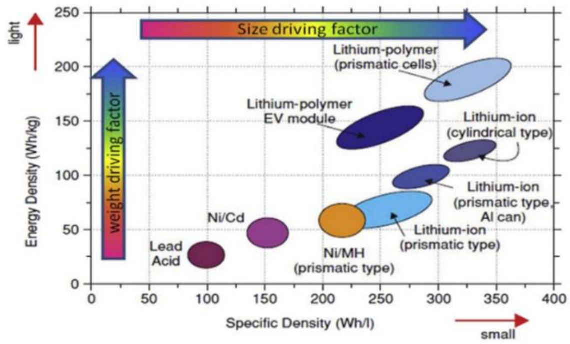


Fig. 4. Energy density and power density for various rechargeable batteries

Figure 4 illustrates the relationship between energy density and power density for various rechargeable battery technologies. A clear overview of the differences between Nickel Cadmium (NiCd) and Nickel-Metal Hydride (NiMH) battery technologies, as well as their suitability for use in photovoltaic (PV) and wind energy systems. NiMH batteries offer improvements over NiCd technology, particularly in terms of energy density and environmental impact. The use of a metal hydride anode eliminates the environmental concerns associated with cadmium, making NiMH batteries more environmentally friendly. These batteries have a negligible memory effect compared to NiCd batteries. Memory effect refers to the phenomenon where a battery gradually loses its capacity to hold a charge if it is repeatedly recharged before being fully discharged. While NiMH batteries offer higher energy density and improved environmental performance, they may have limitations in delivering high peak power and may have a higher self-discharge rate compared to NiCd batteries. Additionally, NiMH batteries may be more susceptible to damage from overcharging. Currently, NiMH batteries may be more expensive than NiCd batteries. However, it is expected that the cost of NiMH batteries will decrease significantly in the future, particularly with advancements in technology and increased adoption in applications such as electric vehicles. NiMH batteries are expected to see increased adoption, particularly in applications where environmental concerns and energy density are important factors. Development programs targeting large-scale applications, such as electric vehicles, are likely to drive down the cost of NiMH batteries and make them more competitive with other battery technologies. The transition from NiCd to NiMH batteries represents a step forward in battery technology, offering improved performance and environmental sustainability. As technology continues to advance and economies of scale improve, NiMH batteries are expected to play an increasingly important role in various energy storage applications, including those in PV and wind energy systems [XXII].

The battery model in Simulink involves defining the behavior of the battery, such as its charge and discharge characteristics, and implementing it using appropriate blocks. Here below is the MATLAB code presented to create a basic battery model in Simulink:

```
% Define battery parameters
battery_capacity = 100; % Battery capacity (Ah)
battery_voltage = 12; % Nominal battery voltage (V)

% Create Simulink model
model = 'battery_model';
open_system(new_system(model));

% Add input signals
add_block('simulink/Sources/Step', [model '/Charging Current']);
add_block('simulink/Sources/Step', [model '/Discharging Current']);
add_line(model, 'Charging Current/1', 'Battery Model/1');
add_line(model, 'Discharging Current/1', 'Battery Model/2');

% Add battery model
add_block('simulink/Continuous/Integrator', [model '/Battery Model']);
set_param([model '/Battery Model'], 'InitialCondition', 'battery_capacity');

% Add battery discharge resistor
add_block('simulink/Commonly Used Blocks/Resistor', [model '/Discharge Resistor']);
set_param([model '/Discharge Resistor'], 'Resistance', num2str(battery_voltage));

% Connect blocks
add_line(model, 'Battery Model/1', 'Discharge Resistor/1');
```

```
% Set simulation parameters
set_param(model, 'StopTime', '10');

% Run simulation
sim(model);

% Plot results
plot(ans.time, ans.battery_model);
xlabel('Time (s)');
ylabel('Battery Charge (Ah)');
title('Battery Model Simulation');
```

The MATLAB battery model is illustrated in Figure below 5. The codes generated above represent the input to the microgrid from BESS.

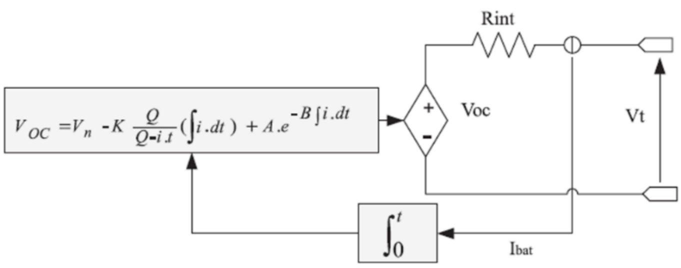


Fig. 5. Simulink Battery Model

The MATLAB Battery Model shown in Figure 5 is a Simulink-based representation of a Battery Energy Storage System (BESS) used in microgrid simulations. This model is designed to simulate the behavior of a battery under different operating conditions, including charging and discharging cycles. It typically includes parameters such as battery capacity, state-of-charge (SOC), voltage, and current, which are crucial for analyzing the performance and interaction of the BESS with the microgrid. The Simulink model in MATLAB consists of interconnected blocks that define the battery's electrical characteristics and dynamic response. It can incorporate various control strategies to manage power flow, optimize battery usage, and ensure efficient energy management in the microgrid. The code generated for this model serves as an input to the microgrid system, determining how the BESS contributes to power stability and energy balancing. In the context of microgrid simulations, the MATLAB battery model helps to evaluate the impact of energy storage on system performance and analyzes scenarios such as peak shaving, load leveling, and support during grid disturbances. By integrating the battery model with other renewable energy sources like solar or wind, the overall stability and reliability of the microgrid can be improved, making it a valuable tool for microgrid design and control strategy development.

V. State of Charge of Battery System

The State of Charge (SoC) of a battery in a microgrid represents the amount of energy stored in the battery relative to its total capacity. It is often expressed as a percentage, ranging from 0% (fully discharged) to 100% (fully charged) [XXIII]. The SoC of a battery can be mathematically expressed using the following formula:

$$SoC = E_{stored}E_{total} \times 100\% \; SoC = E_{total}E_{stored} \times 100\% \quad (5)$$

Where:

- SoC is the State of Charge of the battery (in percentage).
- E_{stored} is the energy stored in the battery (in watt-hours or kilowatt-hours).
- E_{total} is the total energy capacity of the battery (in watt-hours or kilowatt-hours).

Alternatively, if you have the battery's current and voltage information, you can use the following formula to calculate SoC:

$$SoC = \int\{I(t)\cdot V(t)\, dt / C\} \times 100\% \quad (6)$$

Where:

- I(t) is the battery current at time t (in amperes).
- V(t) is the battery voltage at time t (in volts).
- C is the rated capacity of the battery (in ampere-hours).

This formula integrates the product of current and voltage over time to calculate the total energy transferred into or out of the battery, relative to its rated capacity. Both of these expressions provide a mathematical representation of the State of Charge of a battery in a microgrid, allowing you to monitor and manage its energy storage capabilities effectively [XXIV]. Below is the MATLAB code, demonstrating how you can calculate and update the State of Charge (SoC) of a battery in a microgrid simulation:

```
% Define battery parameters
battery_capacity = 100; % Battery capacity in kWh
initial_soc = 0.5; % Initial state of charge (SoC)
charge_efficiency = 0.95; % Charging efficiency
discharge_efficiency = 0.90; % Discharging efficiency

% Define simulation parameters
time_steps = 24; % Number of time steps
load_demand = [10 20 30 25 35 40 45 50 55 60 65 70 75 80 85 90 95 100
95 90 85 80 75 70]; % Load demand profile in kW

% Initialize SoC array
soc = zeros(1, time_steps);
soc(1) = initial_soc;

% Simulate battery operation over time steps
for t = 2:time_steps
    % Calculate net power flow (load demand - renewable generation)
    net_power = load_demand(t) - renewable_generation(t);

    % Calculate charging or discharging power based on net power flow
    if net_power > 0
        % Discharging: decrease SoC
```

```
        discharged_energy = net_power / discharge_efficiency; % Energy
discharged from battery
        soc(t) = soc(t-1) - (discharged_energy / battery_capacity);
    elseif net_power < 0
        % Charging: increase SoC
        charged_energy  =  -net_power  *  charge_efficiency;  %  Energy
charged into battery
        soc(t) = soc(t-1) + (charged_energy / battery_capacity);
    else
        % No net power flow, SoC remains unchanged
        soc(t) = soc(t-1);
    end

    % Ensure SoC stays within 0-1 range
    soc(t) = max(min(soc(t), 1), 0);
end

% Plot SoC over time
time = 1:time_steps;
plot(time, soc, 'LineWidth', 2);
xlabel('Time Step');
ylabel('State of Charge (SoC)');
title('Battery SoC Over Time');
grid on;
```

In microgrid design, the parameters of the battery, such as capacity, initial SoC, charging efficiency, and discharging efficiency can be calculated from the above code which is utilized in this research. To simulate the operation of the battery over a series of time steps, where the load demand varies the SoC accordingly operated within the valid range of 0 to 1.

VI. Droop Control in DC Microgrid

Droop control is indeed commonly used in DC microgrids to regulate voltage and power flow, especially in systems with distributed energy resources (DERs) like photovoltaic (PV) panels, wind turbines, and battery energy storage systems (BESS). In a DC microgrid, multiple DERs may be connected in parallel to a common DC bus. Droop control regulates the voltage of this bus by adjusting the power output of the DERs in response to changes in bus voltage [XXV]. When the bus voltage decreases (due to an increase in load or a drop in generation), the DERs increase their power output to maintain voltage levels. Conversely, when the bus voltage increases, the DERs reduce their power output. Droop control also facilitates power sharing among multiple DERs connected to the same DC bus. Each DER is assigned a droop characteristic, which determines how its power output varies with voltage. The droop characteristic is typically expressed as a percentage change in power output per unit change in voltage. DERs with steeper droop slopes provide more power for a given voltage deviation, while those with shallower droop slopes provide less power. By adjusting their power output based on voltage deviations, DERs with droop control help maintain system stability and balance power supply with demand [XXVI]. This decentralized approach to voltage regulation and power-sharing allows for more flexible and resilient operation of DC microgrids, particularly in scenarios where DERs may vary dynamically due to changing weather conditions or load demands. Droop control ensures that all DERs connected to the DC bus operate in synchronization, with each device responding proportionally to changes in voltage. This coordination prevents instabilities such as voltage fluctuations, frequency deviations, or power imbalances that could otherwise occur if DERs operated independently. Overall, droop control plays a critical role in the efficient and reliable operation of DC microgrids, enabling effective voltage regulation, power sharing, and system stability in the presence of distributed energy resources [XXVII]. Implementing droop control in a microgrid involves programming the droop characteristics for each power source or converter connected to the grid. The droop control in MATLAB/Simulink is presented below:

```
% Define droop characteristics
droop_slope = 0.1; % Droop slope (percentage change in power per
percentage change in voltage)
reference_voltage = 1000; % Reference voltage (V)

% Simulate microgrid behavior
time = 0:0.1:10; % Time vector
load_impedance = 10; % Load impedance (ohms)
load_power = 100; % Load power (W)
grid_voltage = 1000 + 10*sin(2*pi*0.1*time); % Grid voltage (V)

% Calculate power output based on droop control
power_output = load_power + (grid_voltage - reference_voltage) *
droop_slope * load_power / load_impedance;

% Plot results
figure;
plot(time, power_output);
xlabel('Time (s)');
ylabel('Power Output (W)');
title('Microgrid Power Output with Droop Control');
```

Here the Simulink define the droop slope, which represents the percentage change in power per percentage change in voltage. It specifies a reference voltage, which serves as the target voltage for the microgrid. It is simulating the behavior of the microgrid over time, including variations in grid voltage. Based on the droop control algorithm, we calculate the power output of the microgrid as a function of the grid voltage deviation from the reference voltage and the load impedance. Finally, the power output of the microgrid over time can be plotted. This simplified example illustrates the concept of droop control. In a real microgrid implementation, additional factors such as communication between controllers, coordination between multiple power sources, and integration with other control strategies for voltage and frequency regulation are considered.

VII. MATLAB Simulink Model

The model you described is a common approach to battery modeling and simulation, particularly in the context of dynamic systems analysis using software tools like MATLAB/Simulink. Current capacity refers to the maximum amount of current that a battery can deliver under specified conditions. It is an important parameter in battery modeling as it influences the battery's performance and determines its ability to supply power to a load. SOC represents the amount of charge remaining in the battery relative to its full capacity. It is typically expressed as a percentage, with 100% SOC indicating a fully charged battery and 0% SOC indicating a fully discharged battery. SOC is a key parameter in battery management systems, as it provides information about the available energy in the battery and helps optimize charging and discharging strategies. Temperature affects the performance and lifespan of batteries. High temperatures can accelerate chemical reactions within the battery, leading to increased self-discharge rates and reduced capacity. Conversely, low temperatures can decrease battery efficiency and capacity. Temperature monitoring and control are essential for optimizing battery performance and ensuring safe operation. The battery model consists of a controllable voltage source (representing the battery's electromotive force) in series with a resistance (representing internal resistance losses). This simple equivalent circuit model captures the dynamic behavior of the battery during the charging and discharging processes. MATLAB/Simulink provides a versatile platform for modeling and simulating dynamic systems, including battery systems. The battery model described can be implemented using Simulink blocks to simulate the behavior of the battery under different operating conditions and load profiles. This allows engineers to analyze the performance of the battery, optimize control strategies, and design battery management systems. nBattery modeling and simulation play a crucial role in the design, optimization, and control of battery systems for various applications, including renewable energy integration, electric vehicles, and grid-scale energy storage. The model described provides a simplified yet effective representation of battery behavior, allowing engineers to gain insights into battery performance and improve system efficiency and reliability. The MATLAB model for a photovoltaic (PV) and wind energy system with battery energy storage (BESS) is designed and illustrated in below figure 6 to manage the energy flow within the system. The following steps are presented below to design a hybrid microgrid.

- **Define System Parameters**: Define parameters such as PV panel specifications (area, efficiency), wind turbine specifications (rated power, rotor diameter), battery specifications (capacity, efficiency), load profiles, and environmental conditions (solar irradiance, wind speed).

```
% Define system parameters
PV_area = ...; % Area of PV panels (m^2)
PV_efficiency = ...; % Efficiency of PV panels
Wind_turbine_rating = ...; % Rated power of wind turbine (kW)
Wind_turbine_diameter = ...; % Rotor diameter of wind turbine (m)
Battery_capacity = ...; % Capacity of battery (kWh)
```

- **Model Photovoltaic (PV) System**: Implement a model to simulate the power output of the PV system based on solar irradiance and temperature.

```
% PV model
solar_irradiance = ...; % Solar irradiance (W/m^2)
temperature = ...; % Temperature (°C)
```

```
PV_power_output = PV_area * PV_efficiency * solar_irradiance;
```

- **Model Wind Turbine**: Develop a model to simulate the power output of the wind turbine based on wind speed and turbine characteristics.

```
% Wind turbine model
wind_speed = ...; % Wind speed (m/s)

if wind_speed >= cut_in_speed && wind_speed <= rated_speed
    Wind_power_output    =    0.5    *    air_density    *    pi    *
Wind_turbine_diameter^2 * wind_speed^3; % Wind power output (W)
elseif wind_speed > rated_speed && wind_speed <= cut_out_speed
    Wind_power_output = Wind_turbine_rating; % Rated power output (W)
else
    Wind_power_output = 0; % No power output
end
```

- **Model Battery Energy Storage System (BESS)**: Implement a model to simulate the charging and discharging behavior of the battery based on energy flow and battery characteristics.

```
% Battery model
battery_charge = ...; % Battery charge status (kWh)

if battery_charge < Battery_capacity && excess_power > 0
    battery_charge    =    min(battery_charge    +    excess_power    *
efficiency_charge, Battery_capacity); % Charge battery
elseif battery_charge > 0 && load_demand > 0
    battery_discharge    =    min(load_demand,    battery_charge    *
efficiency_discharge); % Discharge battery
    battery_charge  =  max(battery_charge  -  battery_discharge,  0);  %
Update battery charge
end
```

- **Control Algorithms**: Develop control algorithms to manage energy flow within the system, prioritize energy sources, and optimize battery usage.

```
% Control algorithm

if PV_power_output >= load_demand

    excess_power = PV_power_output - load_demand; % Excess power from
PV

    % Battery charge/discharge control

elseif Wind_power_output >= load_demand

    excess_power  =  Wind_power_output  -  load_demand;  %  Excess  power
from wind turbine

    % Battery charge/discharge control

else

    % Insufficient power from renewable sources, rely on battery or
grid

end
```

- **Simulation and Analysis**: Simulate the behavior of the PV-wind-BESS system over time and analyze performance metrics such as energy generation, battery state of charge, and system efficiency.

```
% Simulation loop
for t = 1:num_time_steps
    % Update environmental conditions (solar irradiance, wind speed)
    % Update load demand
    % Run control algorithms
    % Update battery charge status
    % Calculate energy generation from PV and wind
    % Calculate total power output and energy balance
    % Store simulation results
end
```

This is a simplified outline of the code structure for designing a MATLAB model for a PV-wind-BESS system. Creating a MATLAB Simulink model for a PV-Wind-BESS (Battery Energy Storage System) system involves integrating the components of each energy source (PV and wind), the battery storage system, and the associated control algorithms. The MATLAB Simulink model for a PV-Wind-BESS (Battery Energy Storage System) model is presented below.

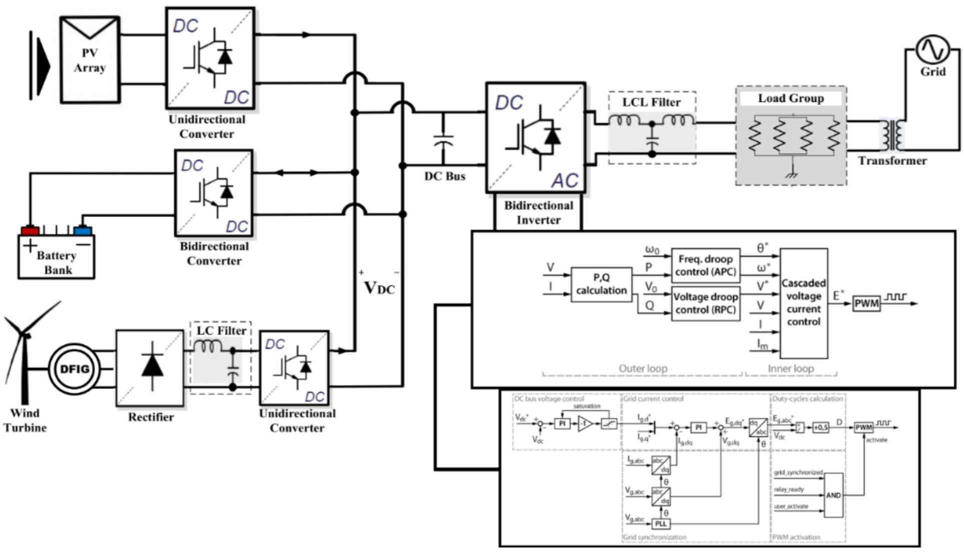


Fig. 6. MATLAB Simulink Model of PV-Wind-BESS Model

Based on the provided description, here are the parameters and their corresponding values for the microgrid system. These parameters define the characteristics and constraints of the microgrid system, including the power ratings of the generators and storage devices, operating frequencies, voltage levels, and battery state of charge limits. They are essential for modeling and simulating the behavior of the microgrid under various operating conditions.

VIII. Simulation Results and Analysis

The microgrid specification includes a PV system with an installed power of 20 kW and a daily production of 82.25 kWh for the simulated day. The wind system has an installed power of 5 kW, producing 45.32 kWh daily. The Battery Energy Storage System (BESS) has a usable energy capacity of 60 kWh and a nominal power of 20 kW, serving as the main BESS. The installed load is 15 kW, with a daily demand of 127.57 kWh. Figures 7 through 13 provide an extensive analysis of the solar PV and wind power systems. Figure 7 shows the daily average power values of the normalized solar PV and wind power time series from 2023 data. Figure 8 illustrates the correlation between cell temperature and ambient temperature. Figure 9 shows the outputs of both the PV and wind portions within this hybrid system. Figures 10(a) and 10(b) present clear-day simulation results using heuristic and optimization approaches, respectively, whereas Figures 11(a) and 11(b) display the cloudy-day simulation results using the same approaches. Lastly, Figure 12 compares the grid cost and grid usage over a 24-hour period.

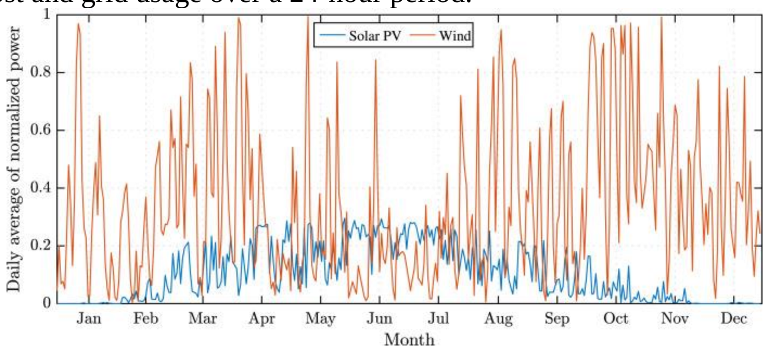


Fig. 7. Normalized solar PV and wind power for daily average power data of 2023

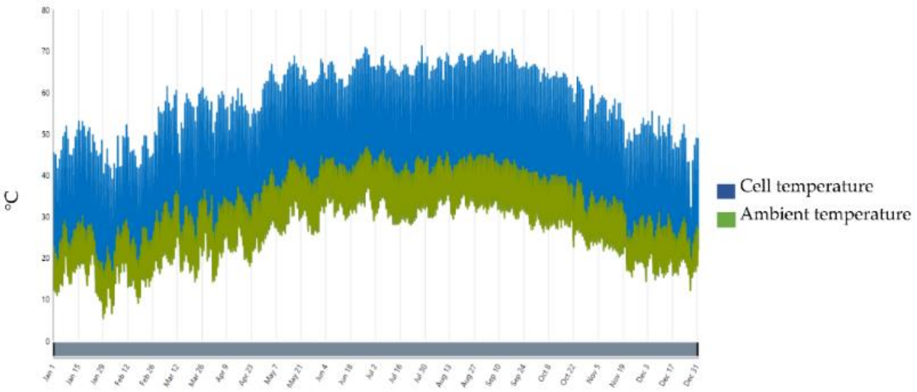
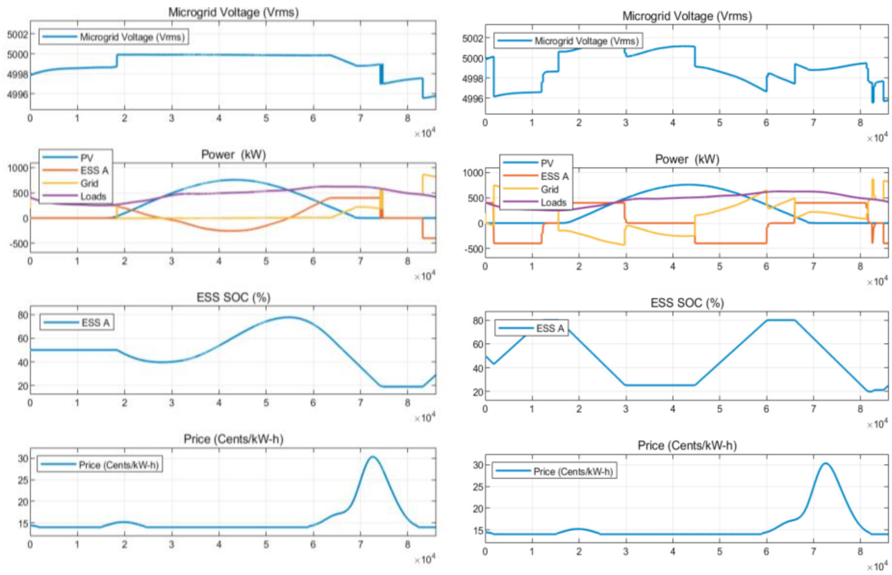


Fig. 8. Relationship between cell temperature to the ambient temperature

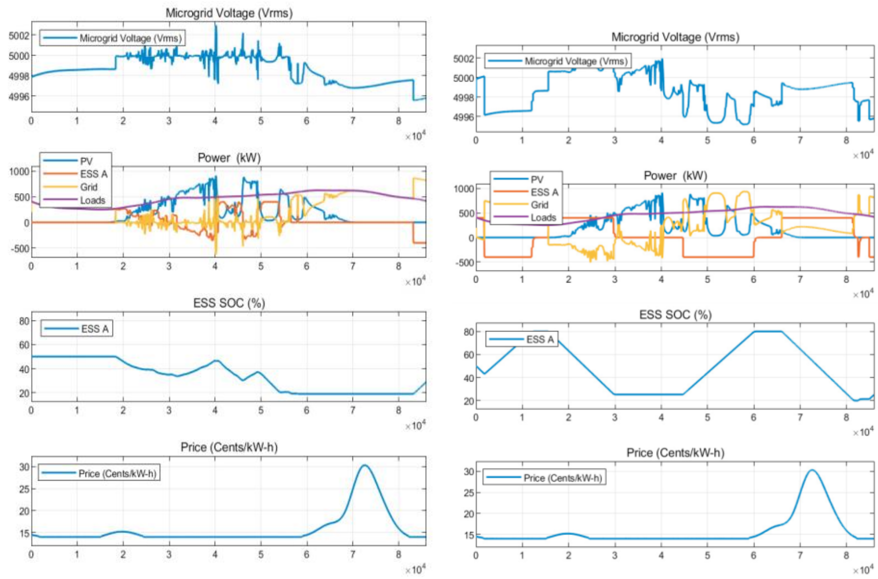
Fig. 9. Average power output for wind and PV in hybrid system



(a) (b)

Fig. 10 (a). Clear-day simulation result using Heuristic Approach

Fig. 10 (b). Clear-day simulation result using the Optimization Approach



(a) (b)

Fig. 11 (a). Cloudy day simulation result using Heuristic Approach

Fig. 11 (b). Cloudy day simulation result using Optimization Approach

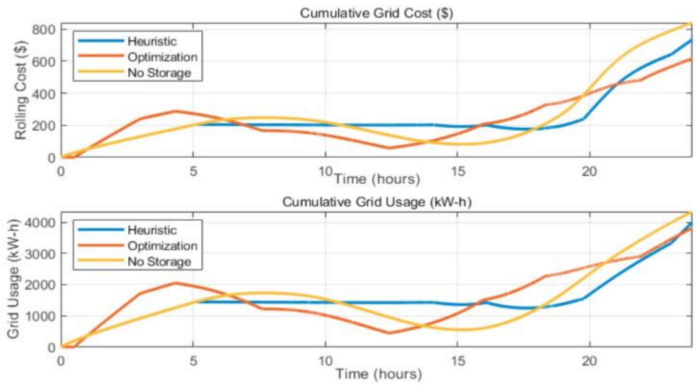


Fig. 12. Cost comparison of grid cost and grid usage for 24 hours

Electricity Purchased (kWh) is the amount of electricity the microgrid buys from the main grid or other sources. If the microgrid is not generating enough power to meet its demand, it will need to purchase additional electricity. Electricity Sold (kWh) is the amount of electricity the microgrid generates and sells back to the main grid or to other consumers. This can be a source of revenue. If the positive net profit scenario indicates that the revenue generated from selling electricity exceeds the cost of purchasing electricity, resulting in profitability for the microgrid operation. Using droop control the net profit is positive which indicates the validation of the proposed microgrid system.

Table 1: Output results using droop control Simulation Techniques

Microgrid Variables	Minimum	Maximum	1st Quarter	2nd Quarter	3rd Quarter	Average
Electricity purchased (kWh)	0.00	230.85	10.20	15.25	34.10	24.68
Electricity sold (kWh)	10.15	111.60	35.30	80.15	84.45	63.33
Net profit (€)	10.15	119.25	25.10	64.90	50.35	38.65 (approx.)
Battery Charging Ah	440.10	995.09	485.12	565.35	650.75	567.07

Table 1 summarizes the output results using droop control simulation techniques for various microgrid variables. It includes ranges and quartiles for electricity purchased, electricity sold, net profit in euros, and battery charging in Ampere-hours (Ah). The table shows that electricity purchased ranged from 0.00 kWh to 230.85 kWh, with quartile values ranging from 10.20 kWh to 34.10 kWh. Electricity sold ranged from 10.15 kWh to 111.60 kWh, with quartile values ranging from 35.30 kWh to 84.45 kWh. Net profit ranged from €10.15 to €119.25, with quartile values ranging from €25.10 to approximately €50.35. Battery charging varied from 440.10 Ah to 995.09 Ah, with quartile values ranging from 485.12 Ah to 650.75 Ah. These findings illustrate the effectiveness of droop control techniques in managing microgrid operations and optimizing performance metrics such as energy transactions and financial outcomes.

VIII. Conclusion

The paper presents an efficient energy management system tailored for a small-scale hybrid microgrid integrating wind, solar, and battery-based energy generation using droop control. The conclusion focuses on the factors contributing to this positive outcome. The research emphasizes the effective implementation of droop control in managing and optimizing energy flow within the microgrid, ensuring efficient utilization of renewable energy sources such as wind and solar. By dynamically adjusting energy generation and storage based on real-time demand and grid conditions, the system minimizes reliance on external electricity purchases and maximizes revenue from selling surplus energy back to the grid or local consumers. This approach not only enhances microgrid stability and reliability but also validates the economic viability of integrating renewable energy with advanced control strategies to achieve sustainable energy management and profitability.

IX. Acknowledgements

The authors would like to express their sincere gratitude to the College of Engineering and Technology, Srinivas University, Mangalore, India, for their valuable support and guidance. Special thanks to the Department of Electrical Engineering, Radhakrishna Institute of Technology and Engineering, Bhubaneswar, Odisha, India, and the Department of Mechanical Engineering, IGIT, Sarang, Dhenkanal, Odisha, India, for providing essential resources and facilities. The authors also acknowledge the support from the Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Bangalore, Karnataka, India, for their valuable collaboration.

Conflicts of interest

All authors declare that they have no conflicts of interest regarding this paper.

References

I. AlKassem, A., Draou, A., Alamri, A., & Alharbi, H. (2022). Design Analysis of an Optimal Microgrid System for the Integration of Renewable Energy Sources at a University Campus. *Sustainability*, 14(7), 4175. https://doi.org/10.3390/su14074175.

II. Almada, J., Leão, R., Sampaio, R., & Barroso, G. (2016). A centralized and heuristic approach for energy management of an AC microgrid. *Renewable and Sustainable Energy Reviews*, 60, 1396–1404.

III. Alvarez, G., Moradi, H., Smith, M., & Zilouchian, A. (2017). Modeling a Grid-Connected PV/Battery Microgrid System with MPPT Controller. *2017 IEEE 44th Photovoltaic Specialist Conference (PVSC)*, 2941–2946.

IV. Arcos-Aviles, D., Pascual, J., Guinjoan, F., Marroyo, L., Sanchis, P., & Marietta, M.P. (2017). Low complexity energy management strategy for grid profile smoothing of a residential grid-connected microgrid using generation and demand forecasting. *Applied Energy*, 205, 69–84.

V. Cabrera-Tobar, A., Massi Pavan, A., Petrone, G., & Spagnuolo, G. (2022). A Review of the Optimization and Control Techniques in the Presence of Uncertainties for the Energy Management of Microgrids. *Energies*, 15(23), 9114. https://doi.org/10.3390/en15239114.

VI. Cecati, C., Dell'Aquila, A., Liserre, M., & Monopoli, V.G. (2003). A passivity-based multilevel active rectifier with adaptive compensation for traction applications. *IEEE Transactions on Industry Applications*, 39(5), 1404–1413.

VII. Franquelo, L.G., Rodriguez, J., Leon, J.I., Kouko, S., & Portillo, R. (2008). The age of multilevel converters arrives. *IEEE Industrial Electronics Magazine*, 2(2), 28–39.

VIII. Genikomsakis, K.N., Lopez, S., Dallas, P.I., & Ioakimidis, C.S. (2017). Simulation of Wind-Battery Microgrid Based on Short-Term Wind Power Forecasting. *Applied Sciences*, 7(11), 1142. https://doi.org/10.3390/app7111142.

IX. Gonzalez, R., Gubia, E., Lopez, J., & Marroyo, L. (2008). Transformerless single-phase multilevel-based photovoltaic inverter. *IEEE Transactions on Industrial Electronics*, 55(7), 2694–2702.

X. Ganthia, B. P., & Upadhyaya, M. (2021). Bridgeless AC/DC Converter & DC-DC Based Power Factor Correction with Reduced Total Harmonic Distortion. *Design Engineering*, 2012-2018.

XI. Ganthia, B. P., Pradhan, R., Das, S., & Ganthia, S. (2017). Analytical study of MPPT based PV system using fuzzy logic controller. *2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)*, 3266-3269. IEEE.

XII. Ganthia, B. P., Sahu, P. K., & Mohanty, A. Minimization Of Total Harmonic Distortion Using Pulse Width Modulation Technique. *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)* e-ISSN, 2278-1676.

XIII. Ganthia, B.P., & Praveen, B.M. (2023). Review on Scenario of Wind Power Generations in India. *Electrical Engineering*, 13(2), 1-27p.

XIV. Ganthia, B.P., Barik, S., & Nayak, B. (2020). Application of hybrid facts devices in DFIG based wind energy system for LVRT capability enhancements. *J. Mech. Cont. Math. Sci.*, 15(6), 245-256.

XV. Ganthia, B.P., Barik, S.K., & Nayak, B. (2020). Transient analysis of grid integrated stator voltage oriented controlled type-III DFIG driven wind turbine energy system. *Journal of Mechanics of Continua and Mathematical Sciences*, 15(6), 139-157.

XVI. Ganthia, B.P., Monalisa Mohanty, Sushree Shataroopa Mohapatra, Rosalin Pradhan, Subhasmita Satapathy, Shilpa Patra, & Sunita Pahadasingh. (2023). Artificial Neural Network Optimized Load Forecasting of Smartgrid using MATLAB. *Control Systems and Optimization Letters*, 1(1), 46-51.

XVII. Ganthia, B.P., Mannam, P., & Manchireddy, S. (2021). Grid Tied PV with Reduced THD Using NN and PWM Techniques. *Design Engineering*, 2019-2027.

XVIII. Hasan, M., Mekhilef, S., & Metselaar, I.H. (2013). Photovoltaic System Modeling with Fuzzy Logic Based Maximum Power Point Tracking Algorithm. *International Journal of Photoenergy*, Article ID 762946, 10 pages. https://doi.org/10.1155/2013/762946.

XIX. Jigar S. Sarda, K., Lee, K., Patel, H., Patel, N., & Patel, D. (2022). Energy Management System of Microgrid using Optimization Approach. *IFAC-Papers On Line*, 55(9), 280-284. https://doi.org/10.1016/j.ifacol.2022.07.049.

XX. Jena, S., Mishra, S., Ganthia, B. P., & Samal, S. K. (2022). Load Frequency Control of a Four-Area Interconnected Power System Using JAYA Tuned PID Controller and Derivative Filter. In *Sustainable Energy and Technological Advancements: Proceedings of ISSETA 2021* (pp. 497-511). Singapore: Springer Singapore.

XXI. Kabat, S.R., Panigrahi, C.K., & Ganthia, B.P. (2022). Comparative analysis of fuzzy logic and synchronous reference frame controlled LVRT capability enhancement in wind energy system using DVR and STATCOM. In *Sustainable Energy and Technological Advancements: Proceedings of ISSETA 2021* (pp. 423-433). Singapore: Springer Singapore.

XXII. Khan, R. A., Farooqui, S. A., Sarwar, M. I., Ahmad, S., Tariq, M., Sarwar, A., Zaid, M., Ahmad, S., & Shah, N. M. A. (2022). Archimedes Optimization Algorithm Based Selective Harmonic Elimination in a Cascaded H-Bridge Multilevel Inverter. *Sustainability*, 14(1), 310. https://doi.org/10.3390/su14010310.

XXIII. Krithiga, G., & Mohan, V. (2022). Elimination of Harmonics in Multilevel Inverter Using Multi-Group Marine Predator Algorithm-Based Enhanced RNN. *International Transactions on Electrical Energy Systems*, Article ID 8004425, 13 pages. https://doi.org/10.1155/2022/8004425.

XXIV. Lai, J-S., & Peng, F. Z. (1996). Multilevel converters—A new breed of power converters. *IEEE Transactions on Industry Applications*, 32(3), 509–517.

XXV. Mannam, P., Manchireddy, S., & Ganthia, B. P. (2021). Grid Tied PV with Reduced THD Using NN and PWM Techniques. *Design Engineering*, 2019-2027.

XXVI. Mohanty, R., Chatterjee, D., Mohanty, S., Dhanamjayulu, C., & Khan, B. (2023). THD Reduction of Improved Single Source MLI Using Upgraded Black Widow Optimization Algorithm. *International Transactions on Electrical Energy Systems*, Article ID 6724716, 16 pages. https://doi.org/10.1155/2023/6724716.

XXVII. Refaai, M. R. A., Dhanesh, L., Ganthia, B. P., Mohanty, M., Subbiah, R., & Anbese, E. M. (2022). Design and Implementation of a Floating PV Model to Analyse the Power Generation. *International Journal of Photoenergy*, Article ID 8004425.