Hybrid Wind-PV-Battery Energy System for DC Load: Simulink Implementation

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***Abstract*—This report presents the design and simulation of a hybrid renewable energy system integrating wind, photovoltaic (PV), and battery storage, modeled in MATLAB/Simulink. The system is designed to power a DC load under varying environmental conditions. Key components, including a wind turbine, Permanent Magnet Synchronous Generator (PMSG), PV array with Maximum Power Point Tracking (MPPT), and battery management system, are designed. Simulation results demonstrate system performance and energy management under fluctuating wind speeds and solar irradiance.**

***Index Terms*—Hybrid energy system, wind energy, photovoltaic (PV), battery storage, DC load, Simulink, renewable energy.**

I. Introduction

The increasing global demand for clean and sustainable energy has highlighted the importance of integrating renewable energy sources such as solar and wind into modern energy systems. Solar photovoltaic (PV) panels and wind turbines are among the most viable renewable energy technologies, offering significant environmental benefits by reducing greenhouse gas emissions and reliance on finite fossil fuels. However, their intermittent and unpredictable nature poses challenges for energy storage and utilization, making it essential to develop efficient hybrid systems that maximize resource utilization and ensure consistent energy availability.

In this project, we focus on the efficient storage and use of energy generated by a hybrid system combining solar PV panels and wind turbines. By leveraging the complementary nature of these resources—solar energy being more abundant during the day and wind energy being available during both day and night—the hybrid system aims to optimize energy capture under varying environmental conditions. To address the complexities of such systems, we have developed a comprehensive SIMULINK model to simulate, analyze, and optimize the performance of the hybrid energy system.

The SIMULINK model enables detailed analysis of energy generation, storage dynamics, and utilization strategies. It provides insights into selecting appropriate energy storage technologies, such as batteries, and determining control strategies to enhance system efficiency and reliability. This project represents a step toward advancing sustainable energy solutions, contributing to global efforts to combat climate change and establish resilient energy systems for a greener future.

II. Working and Methodology

The project started with a model to analyze and optimize solar energy generation and storage. The first model focuses exclusively on optimizing the performance of solar energy generation and utilization without integrating a battery storage system. This standalone solar model evaluates the PV array's performance under varying environmental conditions and utilizes advanced control strategies, such as MPPT, to maximize energy extraction. The second model extends the analysis by incorporating energy storage to assess the dynamics of combined solar and wind energy utilization, ensuring efficient storage and distribution for consistent energy availability.

A. Working

The MATLAB model developed for this project simulates the dynamic behavior of the hybrid solar-wind energy system, integrating generation, storage, and utilization components. The model begins by analyzing site-specific environmental data, including solar irradiance and wind speed profiles, to estimate energy generation potential from solar PV panels and wind turbines. This generation data is coupled with a detailed energy storage subsystem, where various battery technologies are modeled to evaluate their performance in terms of efficiency, capacity, and charge-discharge cycles. Control algorithms are implemented within the model to optimize energy flow, ensuring that surplus energy is stored during peak generation periods and efficiently utilized during demand surges or low-generation periods. Sensitivity analysis is performed to assess the system's performance under different environmental and operational conditions, enabling the identification of strategies to maximize energy utilization and system reliability. This iterative modeling approach provides valuable insights for designing robust and efficient hybrid renewable energy systems as follows:

1) Wind Energy Subsystem:: A wind turbine converts wind kinetic energy into mechanical energy. A Permanent Magnet Synchronous Generator (PMSG) converts the mechanical energy into AC electrical energy. A rectifier converts the AC output to DC and stabilizes the voltage with a DC-link capacitor. The rectified DC power is supplied to the DC bus.

2) Solar PV Subsystem:: A PV array converts solar irradiance into DC power. A boost converter with MPPT control maximizes power output and regulates the voltage for compatibility with the DC bus.

3) Battery Storage Subsystem:: A Lithium-ion battery stores excess energy from the renewable sources or supplies energy to the load when wind and solar power are insufficient. A bidirectional DC-DC converter manages the charging and discharging processes.

4) DC Load:: The load draws power from the DC bus, which is maintained at a stable voltage by coordinating contributions from the wind, solar, and battery subsystems. The system uses a control strategy to prioritize renewable sources and manage battery usage efficiently.

B. Methodology

1) System Design:: Design the wind turbine model, including PMSG and rectifier. Develop the PV array model with MPPT (e.g., Perturb and Observe algorithm). Model the battery storage system with SOC monitoring and bidirectional converter.

2) DC Bus Integration:: Establish a common DC bus for interconnecting wind, PV, and battery subsystems. Design controllers for maintaining stable DC bus voltage.

3) Component Simulation:: Use MATLAB/Simulink to build subsystem models. Input dynamic wind speed and solar irradiance profiles to test real-world performance. Simulate the charging and discharging of the battery in response to energy availability.

4) Control System Implementation:: Apply MPPT algorithms for the PV and wind systems. Use PID controllers for voltage regulation on the DC bus and battery management.

5) Performance Evaluation:: Analyze system behavior under different scenarios, such as varying wind speeds, solar irradiance, and load demands. Evaluate stability, energy efficiency, and reliability metrics.

C. Logic

1) MPPT: This code is a Maximum Power Point Tracking (MPPT) algorithm used to ensure that the solar panels operate at their maximum power point (MPP). The method used here is a variation of the Perturb and Observe (P and O) algorithm, which works by slightly adjusting the operating point and observing how the power changes.
Purpose
The function ‘MPPT Kontrol‘ adjusts the duty cycle (‘duty‘) of a power converter connected to a solar panel. The duty cycle determines how much power is extracted. The goal is to continuously adjust the duty cycle to maximize power output.
Inputs
V: Voltage of the solar panel at the current moment. I: Current of the solar panel at the current moment. deltaD in: The adjustment step size for the duty cycle.
Outputs
duty: The updated duty cycle that moves the system closer to the maximum power point.
Initialization
1. ‘duty init‘, ‘duty min‘, and ‘duty max‘ define the starting, minimum, and maximum allowed duty cycle values: - ‘duty init = 0.05‘ (starting at 5- ‘duty min = 0‘ (duty cycle cannot go below 0). - ‘duty max = 0.75‘ (duty cycle cannot exceed 75

2. Persistent variables (‘Vold‘, ‘Pold‘, and ‘duty old‘) retain their values between function calls: - ‘Vold‘: The last voltage value. - ‘Pold‘: The last power value. - ‘duty old‘: The last duty cycle value.

If these variables are uninitialized (first run), they are set to defaults: - ‘Vold = 0‘, ‘Pold = 0‘, ‘duty old = duty init‘.

Core Logic

1. Calculate current power and changes: - ‘P = V * I‘: Power is calculated as voltage × current. - ‘dV = V - Vold‘: The change in voltage since the last measurement. - ‘dP = P - Pold‘: The change in power since the last measurement.

2. Adjust duty cycle based on power changes: - If there’s a change in power (‘dP not= 0‘): - If power decreases (‘dP less than 0‘): - If voltage decreases (‘dV less than 0‘), reduce the duty cycle (‘duty = duty old - deltaD‘). - If voltage increases (‘dV greater than 0‘), increase the duty cycle (‘duty = duty old + deltaD‘). - If power increases (‘dP greater than 0‘): - If voltage decreases (‘dV less than 0‘), increase the duty cycle (‘duty = duty old + deltaD‘). - If voltage increases (‘dV greater than 0‘), reduce the duty cycle (‘duty = duty old - deltaD‘).

This logic reflects the ”perturb and observe” strategy: - If perturbing (changing) the duty cycle leads to increased power, continue in that direction. - If it leads to reduced power, reverse the perturbation.

3. Clamp the duty cycle: - Ensure ‘duty‘ stays within the allowed range ‘[duty min, duty max]‘: - If ‘duty greater than duty max‘, set ‘duty = duty max‘. - If ‘duty less than duty min‘, set ‘duty = duty min‘.

4.Update Persistent Variables At the end of the function: - ‘duty old‘ is updated to the new ‘duty‘. - ‘Vold‘ and ‘Pold‘ are updated to the current voltage and power.

2) Solar PV Array: The PV array receives irradiance and temperature as inputs, determining its voltage (vpv) and current (ipv) outputs. In this model, the irradiance varies dynamically over 20 seconds as defined. Boost Converter:
A DC-DC boost converter steps up the PV array’s voltage to match the system’s bus voltage. It uses an IGBT (Insulated Gate Bipolar Transistor) as the switching device, controlled by a PWM signal generated by the MPPT algorithm. MPPT Algorithm:
The Maximum Power Point Tracking (MPPT) logic continuously adjusts the duty cycle of the PWM signal. It compares the change in power (P) and voltage (V) to determine the optimal operating point. For instance: If power

decreases with an increase in voltage, the duty cycle is adjusted to decrease voltage. If power increases with an increase in voltage, the duty cycle is adjusted to increase voltage.
Capacitor and Inductor:
The capacitor smoothens the output voltage. The inductor stores and transfers energy to step up the voltage during the switching cycle.

3) Wind Turbine: The turbine generates variable DC power, which is regulated by its own power electronic converter. This subsystem is complementary to the solar PV, supplying power when solar irradiance is low.

4) Battery: The battery acts as an energy storage unit. It smoothens power supply to the load by charging during excess generation and discharging during deficits. Initial SOC is 45 percent, and the system ensures it remains stable and does not overcharge or discharge excessively.Two IGBTs manage the bidirectional flow of energy between the battery and the load/system. The upper IGBT regulates battery charging (when generation exceeds load). The lower IGBT enables battery discharge (when load exceeds generation).

5) Compoenets: 1. MPPT (Maximum Power Point Tracking): The MPPT ensures that the solar PV operates at its maximum power point regardless of irradiance or temperature changes. It dynamically adjusts the PWM duty cycle to optimize power transfer from the PV array to the bus.
2. PWM (Pulse-Width Modulation): PWM is the technique used to control the switching of the IGBTs. The duty cycle (ratio of ON to OFF time) determines the boost converter's output voltage and ensures the battery's charging/discharging current is appropriately regulated.
3. IGBT (Insulated Gate Bipolar Transistor): IGBTs are key switching elements used in the boost converter and battery control circuits. They toggle between ON and OFF states based on the PWM signal, enabling efficient energy transfer with minimal losses. In the boost converter, the IGBT controls the energy flow from the PV array to the bus. In the battery circuit, IGBTs manage the charge/discharge cycles by regulating the current flow direction.
4. Battery and SOC Control: The battery serves as a buffer, absorbing excess energy or supplying it when needed. The control system monitors SOC, ensuring safe operation by preventing overcharging or deep discharge.
5. Hybrid Power Coordination: The solar PV and wind subsystems work in tandem to supply power to the load and charge the battery. When solar irradiance decreases (e.g., due to shading), the wind turbine compensates. The control system prioritizes maintaining a steady bus voltage (48V) while efficiently utilizing available resources.

III. Advantages

A. Complementary Energy Profiles

Solar PV: Generates energy during the day and peaks at noon when sunlight is strongest.
Wind Energy: Often produces power during evenings, nights, or periods of low solar irradiance, depending on local wind patterns.
By combining the two sources: The hybrid system reduces dependence on a single energy source, improving overall energy utilization throughout the day and seasons.

B. Reduced Energy Losses

In standalone systems, excess energy often goes unused due to lack of storage or limited load matching.In a hybrid setup:
Battery Storage: Stores excess energy from PV or wind, reducing energy wastage.
Load Balancing: Surplus from one source compensates for deficits in the other.

C. Increased Power Supply Reliability

Hybrid systems are less vulnerable to intermittency. For instance: A sudden drop in solar output due to cloud cover can be compensated by wind energy. Battery backup ensures continuous power delivery even when both sources are insufficient.

D. Efficiency Gains from Power Electronics

Integrated power converters and DC bus systems optimize the power transfer between sources and the load.
MPPT: Ensures each source operates at maximum efficiency.
DC-DC Converters: Minimize losses during voltage regulation.

E. Increased Capacity Factor:

Capacity factor measures how effectively a system produces energy compared to its maximum theoretical output. Hybrid systems achieve higher capacity factors due to complementary source utilization and reduced idle times.

F. Lower Specific Costs:

The hybrid system spreads infrastructure costs (e.g., inverters, controllers) across multiple sources, reducing the cost per watt of energy produced.

G. Environmental Benefits:

Reduced reliance on fossil fuel backup minimizes carbon emissions, enhancing the system's overall sustainability efficiency.

H. Wind Energy Contributions:

Maintains energy output during periods of low solar irradiance. Exploits high-energy-density wind during storms or windy seasons, reducing battery drain.

I. Solar PV Contributions:

Provides consistent energy output during clear daytime conditions, ensuring the wind turbine can operate efficiently (e.g., reduced idle time in low-wind scenarios).

J. Battery Contributions:

Reduces curtailment by storing excess energy from PV and wind. Smooths out transient fluctuations in power supply, enhancing grid or load stability.

IV. Results and Discussion

A. Circuit

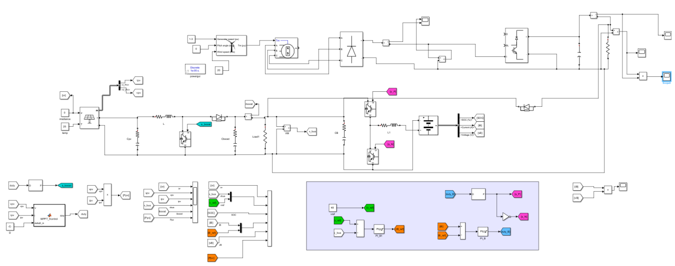

Fig. 1. Model

B. SOC

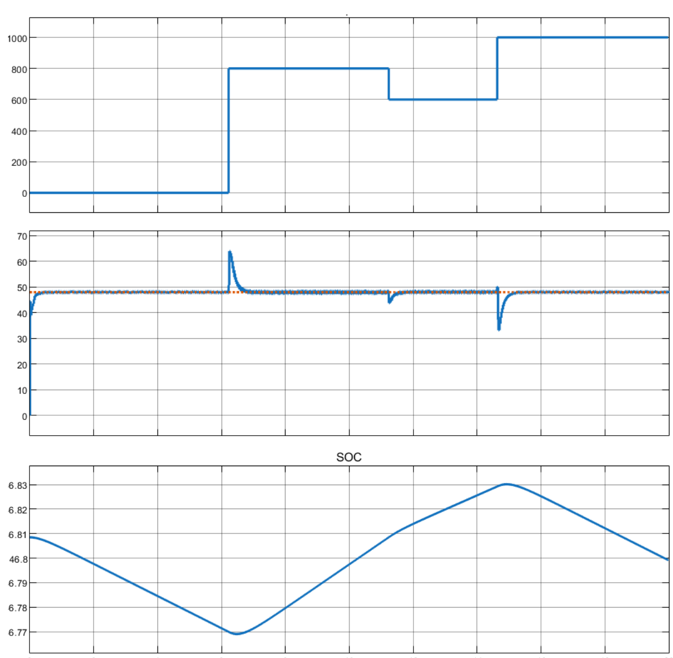

Fig. 2. IRR——V Bus——SOC

The top graph shows the solar irradiance profile over time, representing the environmental conditions affecting the PV generation. Corresponding changes in voltage and SOC demonstrate the hybrid system's ability to adapt to varying conditions. Stable DC bus voltage during irradiance fluctuations highlights the system's reliability and effectiveness in maintaining power delivery to the load.

The middle plot represents the relationship between the solar irradiance levels and the DC bus voltage in the hybrid system. The voltage at the DC bus remains relatively stable around 48-50V despite variations in irradiance. However, sharp transients are observed at points where irradiance changes abruptly. This indicates that the MPPT (Maximum Power Point Tracking) controllers for the solar PV system respond quickly to irradiance changes, maintaining near-constant voltage output. Minor oscillations are due to dynamic adjustments by the controllers.

The bottom graph illustrates the state of charge (SOC) of the battery over time. Initially, the SOC decreases due to high load demand and insufficient generation from the hybrid sources. As the irradiance increases, the PV system generates more power, and surplus energy charges the battery, causing the SOC to rise. After the peak, the SOC stabilizes and begins to decline when generation falls short of demand, demonstrating the battery's role in compensating for power deficits.

C. Response of Different Batteries

The variation in initial SOC (around 45 percent, but not exactly) arises from how Simulink models the internal parameters of each battery, such as open-circuit voltage (OCV), capacity, and initial conditions. These parameters slightly adjust the SOC based on the battery's equivalent circuit representation. The differences in SOC impact charging/discharging behavior, influencing how quickly each battery can supply or absorb energy

1) Lithium-Ion Battery in the Circuit:: Initial Response: Lithium-ion batteries show the most accurate SOC initialization due to their precise modeling of OCV-SOC relationships. The SOC deviation is minimal, reflecting real-world efficiency.

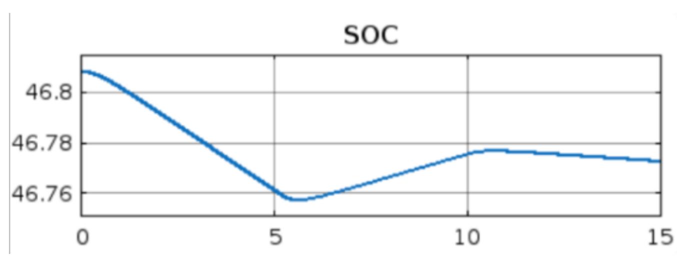

Fig. 3. SOC

Under Varying Irradiance: At 0 irradiance, it provides stable discharge with minimal voltage sag, efficiently supporting the load.
At 700 irradiance, rapid charging occurs, with high efficiency

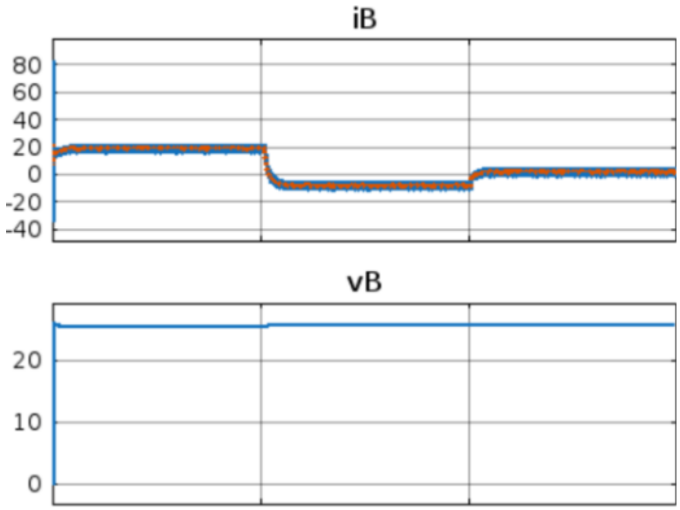

Fig. 4. IB and VB

and minimal losses.
At 400 irradiance, it balances charge/discharge effectively, maintaining system stability.
Implications for this Circuit: Best performance for hybrid renewable systems due to high energy density, fast response, and low self-discharge rates.
Lithium-ion batteries are an excellent choice due to their high energy density, fast charge-discharge rates, and superior efficiency (90 percent or higher). These characteristics make them ideal for handling frequent power variations caused by changing irradiance. They also have a long cycle life, allowing them to endure repeated charging and discharging without significant performance loss. However, they are more expensive and can be sensitive to extreme temperatures, requiring protective measures for outdoor use

2) Lead-Acid Battery in the Circuit:: Initial Response: Lead-acid batteries are modeled with higher internal resistance, leading to a lower effective SOC at startup. Their slow charge acceptance impacts initial performance. Under

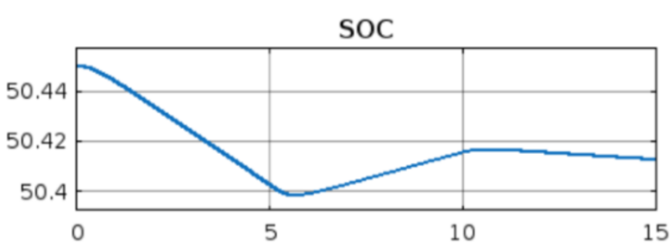

Fig. 5. SOC

Varying Irradiance: At 0 irradiance, the battery discharges faster due to higher internal losses.
At 700 irradiance, charging is sluggish; the SOC may rise gradually, limiting the availability of stored energy.

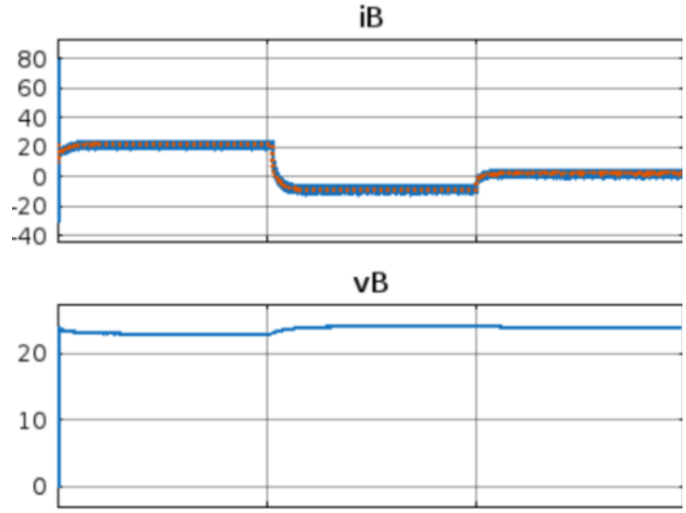

Fig. 6. IB and VB Lead Acid

At 400 irradiance, the battery struggles to adapt quickly, with noticeable efficiency losses during partial state-of-charge operations.
Implications for this Circuit: Good for low-cost, stationary systems but unsuitable for rapid charge/discharge scenarios or fluctuating conditions.
Lead-acid batteries are a more cost-effective option and are widely used in renewable energy systems. They are robust and simple to maintain but have a lower energy density and shorter cycle life compared to Lithium-ion batteries. Their charging efficiency is also lower, which may result in energy losses during prolonged periods of low solar input. Additionally, their slower response to rapid power fluctuations might make them less ideal for hybrid systems with high variability.

3) Ni-Cd Battery in the Circuit:: Initial Response: Ni-Cd batteries handle rapid charge/discharge cycles well and have high tolerance for overcharging. However, their SOC initialization may slightly deviate due to inherent modeling of memory effects.

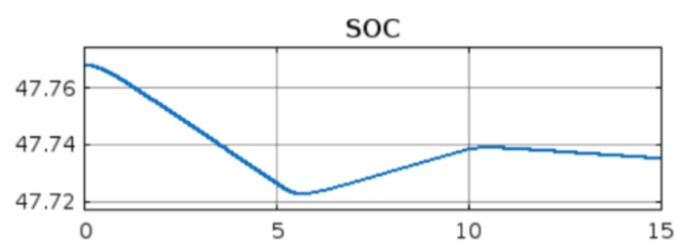

Fig. 7. SOC

Under Varying Irradiance:
At 0 irradiance, the battery discharges steadily, maintaining load power until it approaches its depth-of-discharge (DOD)

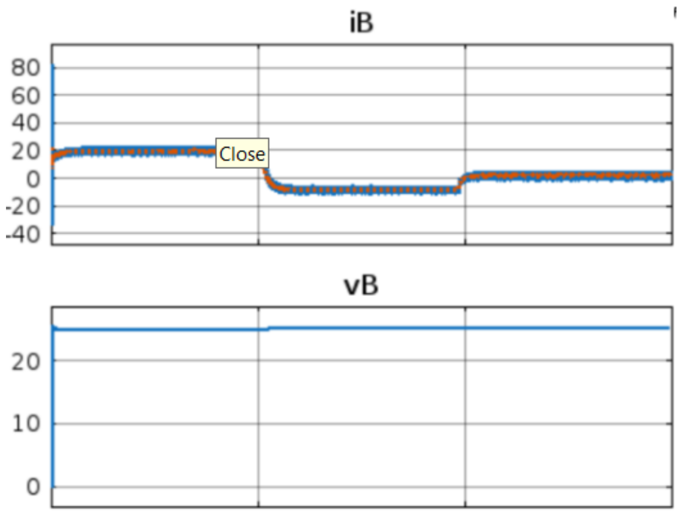

Fig. 8. IB and VB

limit.
At 700 irradiance, charging occurs efficiently, but overcharging protection kicks in to prevent damage.
At 400 irradiance, it balances between charge and discharge, maintaining system equilibrium.
Implications for this Circuit: High durability and lower sensitivity to fluctuations make it robust for hybrid systems but less efficient than newer technologies.
Nickel-Cadmium (Ni-Cd) batteries are known for their durability and ability to handle harsh environmental conditions. They perform well in a wide temperature range and have a long cycle life. However, their energy density is lower than Lithium-ion batteries, and they suffer from a memory effect, meaning their capacity can reduce over time if not fully discharged regularly. Furthermore, Ni-Cd batteries have environmental concerns due to their toxic cadmium content, making disposal and recycling more challenging.

4) Nickel-Metal Hydride (Ni-MH) Battery in the Circuit:: Initial Response: Ni-MH batteries may initialize with slightly lower SOC due to their higher self-discharge and thermal characteristics. Their SOC behavior varies more than others.

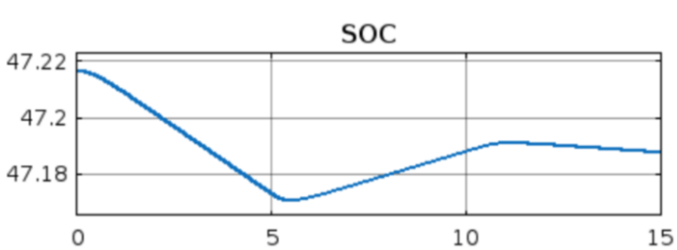

Fig. 9. SOC

Under Varying Irradiance:
At 0 irradiance, they discharge moderately but exhibit higher

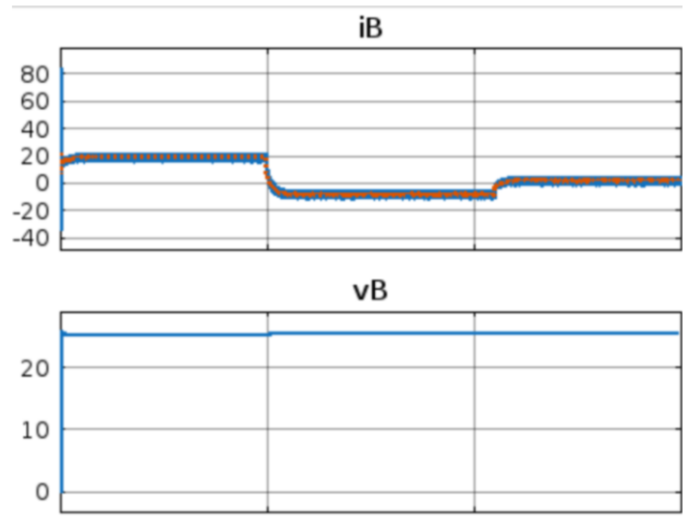

Fig. 10. IB and VB

losses due to internal heating.
At 700 irradiance, charging occurs efficiently but can generate heat, potentially limiting long-term performance.
At 400 irradiance, they adapt to fluctuating loads reasonably well, though less efficiently than lithium-ion.
Implications for this Circuit: Moderate performance with decent adaptability but may require cooling and careful charge management.
Nickel-Metal Hydride (NiMH) batteries offer a balance between cost and performance. They have a higher energy density and longer cycle life than Lead-acid batteries but are less efficient and have a higher self-discharge rate compared to Lithium-ion. This makes them suitable for moderate fluctuations but less ideal for handling rapid changes in load or power supply. They are also more temperature-stable than Lithium-ion batteries, which can be advantageous in outdoor systems.

V. CONCLUSION

This report presents a comprehensive analysis of a hybrid renewable energy system consisting of a wind turbine, solar PV system, and battery storage connected to a DC load. The simulation results demonstrate the effectiveness of this hybrid system in maintaining a stable power supply, with the battery playing a crucial role in compensating for intermittent generation from the wind and solar resources. The hybrid system exhibits enhanced energy efficiency, leveraging the complementary nature of wind and solar power to ensure continuous energy availability.

Key findings include the stable DC bus voltage despite fluctuating irradiance and the efficient battery charge-discharge cycles observed in the SOC profile. However, some transients were noted, which could be further optimized by fine-tuning the controllers. The results validate that hybrid systems can significantly improve energy reliability, efficiency, and sustainability compared to conventional single-source renewable systems. This work underscores the potential of hybrid wind-PV-battery systems to contribute to a more resilient and cost-effective renewable energy infrastructure.

Further research and improvements in controller algorithms and energy management systems could enhance performance, minimize power fluctuations, and increase the overall efficiency of such systems, making them more viable for widespread deployment in both residential and industrial applications.

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