



A Hybrid Solar and Hydrodynamic Energy Harvesting System with Intelligent Battery Management for Autonomous Marine Vessels

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ABSTRACT: This paper presents a hybrid battery monitoring and charging system for autonomous marine vessels, integrating photovoltaic (PV) modules with a hydrodynamic impeller. The system addresses limitations of conventional engine-dependent charging by harvesting solar energy during idling and hydropower from water flow during vessel motion. A microcontroller monitors battery voltage, current, and temperature, implementing a smart switching algorithm to select the optimal charging source dynamically. Protection features including overcharge prevention, deep discharge cutoff, and thermal regulation enhance battery lifespan. Real-time operational parameters are displayed for user awareness. This dual-mode approach minimizes fossil fuel dependency, ensuring reliable power for navigation, propulsion, and communication systems. The proposed solution is ideal for fishing vessels, autonomous robots, and small transport boats requiring sustainable and self-sufficient power management.

Keywords: Hybrid energy harvesting, photovoltaic module, hydrodynamic impeller, battery monitoring system, autonomous marine vessel, renewable energy, charge controller, embedded system.

1. Introduction

The maritime sector is undergoing rapid transformation toward electrification and automation, driven by urgent environmental imperatives. The International Maritime Organization reports that shipping accounts for approximately 2.5% of global CO₂ emissions, accelerating the need for cleaner energy alternatives in marine applications [1]. Small-scale vessels, including fishing boats, autonomous surface vehicles, and inland transport craft, increasingly depend on battery-powered systems. However, ensuring continuous power availability in remote marine environments remains a critical technical challenge.

Conventional vessels rely on engine-driven alternators for battery charging, a method constrained by fossil fuel consumption and

operational limitations. Charging occurs only when the main engine runs, leaving batteries vulnerable to depletion during stationary periods. This compromises essential functions such as navigation lights, communication equipment, and monitoring systems. Manual battery replacement or shore-based charging introduces logistical complexity and operational downtime, particularly problematic for autonomous vessels designed for extended missions [2].

Renewable energy integration offers a sustainable pathway forward. Solar photovoltaic technology provides clean energy during daylight hours but suffers from intermittency due to weather and diurnal cycles [3]. Hydrodynamic energy harvesting utilizing water-flow impellers capitalizes on vessel motion to generate electricity, remaining viable whenever the vessel is underway regardless of solar availability [4].

Combining these sources creates a complementary harvesting framework: solar captures energy during idling, while hydro generation activates during transit, ensuring continuous charging across diverse operational states.

Effective hybrid energy management requires intelligent control systems capable of monitoring battery status and optimizing charging decisions in real-time. Parameters including state of charge, voltage, current, and temperature must be continuously assessed to implement protection mechanisms such as overcharge prevention and deep discharge cutoff [5]. Embedded microcontroller platforms provide cost-effective means of implementing such intelligent architectures in small marine vessels.

This paper presents a hybrid battery monitoring and charging system combining photovoltaic modules with hydrodynamic impellers under microcontroller supervision. The architecture continuously harvests energy from both sources, dynamically selecting the optimal charging pathway based on real-time availability and battery condition. Comprehensive protection features safeguard battery health while an integrated display provides operational visibility. The system aims to reduce fossil fuel dependency, extend mission durations, and enhance reliability for diverse marine applications.

1.1 Motivation

- Traditional boats depend on fuel-powered alternators or manual battery charging, leading to frequent power shortages and high maintenance
- Solar-only systems fail to provide consistent charging due to weather changes, nighttime, and shaded marine environments

- Marine vessels need uninterrupted power for critical functions like navigation, communication, and onboard electronics
- A hybrid system combining solar and hydropower ensures continuous energy generation whether the boat is stationary or moving
- Intelligent monitoring and automatic source selection extend battery life, enhance safety, and improve overall system reliability

1.2 Objectives

- Develop a hybrid battery charging and monitoring system using renewable energy for marine applications
- Integrate solar PV and hydrodynamic impeller sources to enable continuous and reliable battery charging
- Design an Arduino-based controller that automatically selects the most efficient charging source
- Implement real-time monitoring of battery voltage, current, and temperature
- Incorporate safety features including overcharge protection, low-voltage cutoff, and thermal shutdown
- Display real-time system parameters on an LCD/OLED screen for user convenience and awareness

1.3 Literature Survey

[1] H. S. Nomak and İ. Çiçek, "Decarbonizing a Sailboat Using Solar Panels, Wind Turbines, and Hydro-Generation for Zero-Emission Propulsion," *Sustainability*, vol. 17, no. 20, pp. 9050, Oct. 2025.

This paper presents a zero-emission propulsion system for a 12.5 m sailing yacht integrating static solar panels and wind turbines with dynamic hydro-generators and a regenerative propeller.

The study replaces conventional diesel engines with an electric drivetrain powered entirely by renewable sources. Simulations using real mid-latitude meteorological data demonstrated that during 24-hour voyages, propulsion and hotel loads were sustained solely by onboard renewables, with battery state of charge remaining above 28-46%. The findings confirm that integrated multi-source renewables can provide complete energy autonomy for sailing vessels, with scalability to eco-tour boats and ferries

[2] Y. Belkhier, S. Tamalouzt, E. Delaleau, G. Yao, A. Mamoune, and M. E. H. Benbouzid, "Hybrid Offshore Wind-Hydrogen Microgrid for Marine Docking Stations: Design and Energy Management for Economic Operation," in *Proc. IECON 2025 – 51st Annual Conf. IEEE Industrial Electronics Society*, 2025, pp. 1-6.

This research presents the design and optimization of a hybrid microgrid system integrating offshore wind energy, water-fed electrolyzers, hydrogen storage, fuel cells, and battery storage for marine docking stations. The system supplies sustainable energy to charging stations servicing both surface and underwater electric vehicles. Offshore wind power drives seawater electrolysis to produce hydrogen for storage, demonstrating a novel approach to marine energy infrastructure that combines multiple renewable sources with hydrogen as an energy carrier for extended operational capability.

[3] Y. Luo, S. Fang, L. Kong, T. Niu, and R. Liao, "Dynamic Power Management of Shipboard Hybrid Energy Storage System Under Uncertain Navigation Conditions," *IEEE Trans. Transportation Electrification*, vol. 10, no. 2, pp. 3138-3152, June 2024.

This paper proposes a dynamic power management method for shipboard hybrid energy storage systems (HESS) under uncertain navigation conditions. A multiscenario

propulsion power model quantifies the impacts of deterministic navigation factors separately from uncertain elements. A dynamic battery model considering internal states coupling accurately estimates available power range in harsh marine environments. Results demonstrate: 1) propulsion power model achieves 98.7% test accuracy; 2) battery model reduces average estimation error by 1.622%; 3) power allocation strategy improves mean DC voltage by 17.39% and reduces battery power fluctuations by 18.4%

[4] Y. Liu, Z. Tian, J. Yang, and Z. Lin, "Data-Driven Evolutionary Game-Based Model Predictive Control for Hybrid Renewable Energy Dispatch in Autonomous Ships," in *Proc. 4th Int. Conf. New Energy System and Power Engineering (NESP 2025)*, Fuzhou, China, 2025, pp. 482-490.

This study proposes a data-driven Evolutionary Game-Based Model Predictive Control (EG-MPC) framework for energy dispatch in autonomous ships powered by hybrid renewable energy systems. The architecture integrates solar PV, wind turbines, battery storage, and diesel backup. The framework minimizes operational costs considering battery degradation and diesel fuel expenses while leveraging real-world data for enhanced modeling accuracy. Simulation results demonstrate that EG-MPC achieves cost-effective, reliable, and adaptive energy dispatch, outperforming conventional rule-based and standard MPC approaches under uncertainty conditions

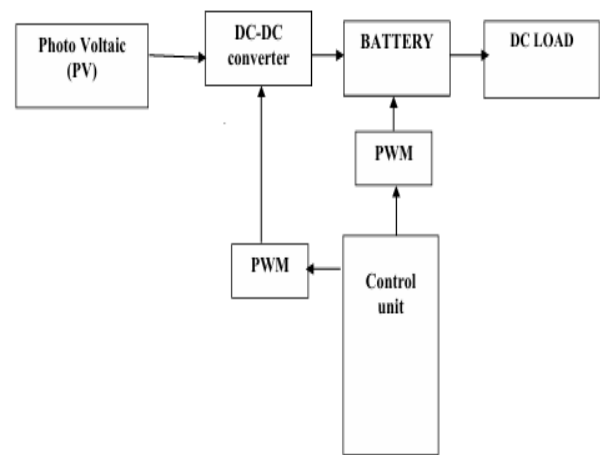
[5] S. Varotto, V. Trovato, and E. Kazemi Robati, "Optimal Sizing and Energy Management of Battery Energy Storage Systems for Hybrid Offshore Farms," in *Proc. 22nd IEEE Mediterranean Electrotechnical Conf. (MELECON 2024)*, Porto, Portugal, 2024, pp. 390-395.

This paper investigates the financial benefits of installing battery energy storage systems behind the meter of hybrid offshore farms combining

wind turbines and floating photovoltaic panels. A mixed integer linear programming optimization model assesses optimal investment and operation decisions for energy storage, subject to technical constraints including connection capacity limitations and grid-imposed ramping requirements. Three battery configurations are analyzed: offshore co-located with the hybrid farm, onshore at grid connection point, and distributed across both locations. Results demonstrate significant financial value from battery installation, including reduced renewable energy curtailment.

2. Existing System

- Existing electric vehicle charging stations primarily depend on the conventional power grid, resulting in high operational costs and increased grid stress during peak demand periods
- Some systems incorporate photovoltaic arrays for renewable energy, but lack efficient control mechanisms to handle the fluctuating nature of solar power due to weather variations
- Conventional systems use basic control methods for regulating DC bus voltage and power distribution, which are not optimized for dynamic conditions like changing solar irradiance and grid voltage fluctuations
- These systems cannot effectively respond to unpredictable EV charging demands, leading to inefficient power allocation and potential service interruptions
- Energy storage components, when present, are poorly managed and fail to balance energy flow properly or maintain voltage stability under varying load conditions



2.1 Disadvantages of Existing System

- High dependence on conventional power grid leads to increased electricity costs and carbon footprint
- Lack of intelligent control mechanisms results in inefficient power distribution under varying solar irradiance and load conditions
- Unable to handle unpredictable EV charging demands, causing voltage fluctuations and grid instability
- Poor energy storage management reduces battery lifespan and fails to maintain stable power supply during peak demand
- No real-time monitoring or automatic source selection, leading to energy wastage and reduced system reliability

3. Proposed System

- Integrates dual renewable energy sources: solar PV panels for harvesting energy during stationary periods and hydrodynamic impeller for generating power when the boat is in motion
- Utilizes Arduino-based microcontroller as central control unit to continuously monitor battery voltage, current, and temperature in real-time

- Implements intelligent switching algorithm that automatically selects the optimal charging source based on source availability and battery condition
- Provides comprehensive battery protection features including overcharge prevention, deep discharge cutoff, and thermal shutdown to extend battery lifespan
- Displays real-time operating parameters such as voltage, current, and charging status on LCD/OLED screen for user awareness
- Ensures continuous power availability for critical marine systems including navigation lights, communication devices, and propulsion motors
- Reduces dependency on fossil fuels by maximizing renewable energy harvesting from both solar and hydrodynamic sources
- Offers a cost-effective and scalable solution suitable for fishing vessels, autonomous marine robots, and small transport boats

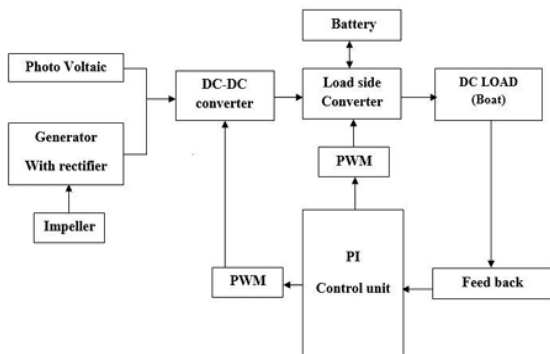


Table 2: Module Description

Component	Description
Photovoltaic (PV) Array	A panel consisting of multiple solar cells connected in series and parallel to convert sunlight directly into electrical energy. It generates DC power when exposed to solar radiation during daytime or when the boat is stationary. Output voltage and current vary with light intensity.
Impeller DC Generator	A waterproof generator mounted below the waterline containing a rotor with blades that spin when water flows past during boat motion. The rotating shaft drives a permanent

3.1 Advantages

- Ensures continuous battery charging through dual renewable energy sources regardless of boat motion or weather conditions
- Extends battery lifespan by preventing overcharge, deep discharge, and overheating through intelligent monitoring
- Reduces fuel costs and carbon emissions by minimizing dependence on engine-driven alternators
- Provides real-time system status display for easy user monitoring and quick fault detection
- Offers a reliable, low-maintenance, and scalable solution suitable for various small marine vessels

Table 1: Hardware and Software Specification

Hardware Specification	Software Specification
Photovoltaic (PV) Array Impeller DC Generator DC-DC Converter (Boost Converter) MPPT DC Bus DC Motor (Load) Control Unit	MATLAB

Component	Description
	magnet DC generator producing electricity proportional to boat speed. Converts kinetic energy of moving water into electrical energy.
DC-DC Boost Converter	An electronic circuit that steps up lower DC voltage from sources like the impeller generator (typically 6-12V) to a higher regulated voltage required for battery charging (14.4V for 12V systems). Uses switching devices, inductor, and capacitor to achieve voltage conversion with high efficiency.
MPPT Charge Controller	Maximum Power Point Tracker is an intelligent DC-DC converter that continuously adjusts electrical operating point of PV panels to extract maximum available power under varying sunlight and temperature conditions. Ensures optimal energy harvest from solar source.
DC Bus	A common power distribution line or connection point where multiple energy sources (PV and impeller) and loads (battery and motor) are interconnected. Acts as a central hub for power flow management and voltage stabilization.
DC Motor (Load)	Represents the propulsion motor or auxiliary equipment such as navigation lights, bilge pumps, or communication devices that consume electrical power. Used for testing system performance under various load conditions.
Control Unit	The brain of the system consisting of Arduino microcontroller along with voltage dividers, current sensors, and relay drivers. Reads input from sensors, executes control algorithm, makes decisions for source selection, manages protection features, and drives the display module.

3.2 PI Algorithm

The following steps are followed for designing the PI controller:

1. Obtain the open loop transfer function of the given higher order system
2. Form the closed loop transfer function and analyze its step response
3. Check if the response meets desired specifications (rise time, settling time, overshoot)
4. If specifications are not satisfied, derive a reduced order model for simpler controller design
5. Calculate initial values of proportional gain (K_p) and integral gain (K_i) using pole-zero cancellation method
6. Cascade the PI controller with reduced order model and simulate closed loop response using initial K_p and K_i values
7. Optimize controller parameters using Genetic Algorithm (GA) to meet required specifications
8. Apply the optimized K_p and K_i values to cascade the controller with original higher order system
9. Obtain and analyze the closed loop step response of original system with optimized controller
10. If specifications are met, finalize controller design; otherwise, repeat tuning process until requirements are satisfied.

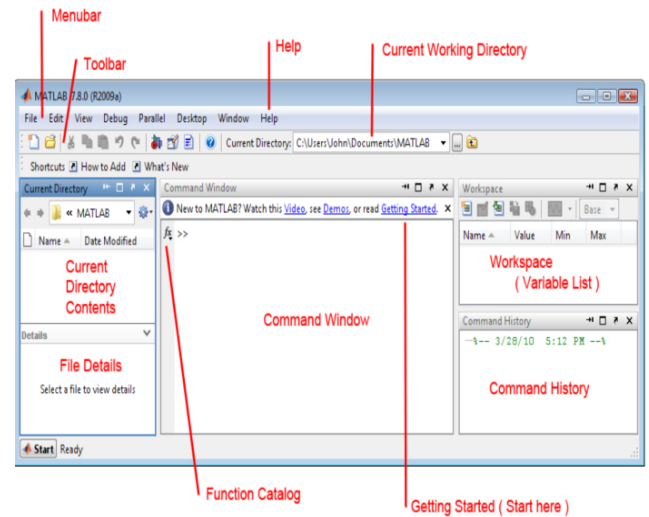
3.3 Software Description

MATLAB (Matrix Laboratory) is a high-performance programming platform specifically designed for engineering and scientific computing. In this project, MATLAB along with its Simulink toolbox serves as the primary simulation environment for designing, modeling, and analyzing the hybrid battery charging system before hardware implementation.

The photovoltaic array is modeled using mathematical equations representing solar cell characteristics under varying irradiance and temperature conditions. Similarly, the hydrodynamic impeller generator is modeled as a variable DC source whose output voltage changes with water flow rate, simulating real-world boat motion scenarios. The DC-DC boost converter and MPPT controller are designed using power electronics blocks to verify voltage regulation and maximum power point tracking performance.

The PI controller for the charging system is designed and tuned within MATLAB using the method described previously. The open loop transfer function of the system is derived, and controller parameters K_p and K_i are optimized using Genetic Algorithm toolbox to achieve desired transient response specifications including minimal overshoot and fast settling time. The complete closed loop system is simulated to verify battery charging behavior under varying source availability and load conditions.

MATLAB's plotting capabilities allow visualization of critical parameters such as battery voltage, charging current, state of charge, and source contributions over time. This enables thorough performance analysis and validation of the control algorithm before actual hardware implementation, significantly reducing development time and cost while ensuring system reliability.



4. Simulation Description

The proposed hybrid battery monitoring and charging system is simulated using MATLAB/Simulink to validate its performance before hardware implementation. The simulation model integrates all key components of the actual system as follows:

4.1 PV Array Subsystem

A photovoltaic array is modeled using solar cell blocks with parameters matching the selected panel rating. Irradiance and temperature inputs are varied during simulation to emulate real-world conditions such as passing clouds, morning/evening variations, and shaded environments. The PV output is connected to an MPPT controller that continuously tracks maximum power point using Perturb & Observe algorithm.

4.2 Hydrodynamic Impeller Generator Subsystem

The impeller DC generator is modeled as a variable speed DC source whose output voltage and current change with water flow velocity. A lookup table maps boat speed (knots) to generator output, simulating real conditions from slow trolling (2-3 knots) to planing speeds (15-20 knots). The generator output feeds through a boost converter to match battery charging voltage requirements.

4.3 Power Conversion Stage

The simulation includes multiple converter blocks as shown in your diagram:

- **Boost Converter 1:** Steps up impeller generator voltage
- **DC/DC Converters:** Regulate power from both sources to common DC bus
- **DC/AC Converters:** Included for potential AC load testing
- **Rectifier:** Converts any AC generation back to DC for battery charging

4.4 Battery and Load Management

A battery block models the energy storage with configurable parameters (capacity, initial SOC, internal resistance). The DC machine represents propulsion load, with speed controlled through PWM signals. Current and voltage sensors throughout the model feed data to the control algorithm block.

4.5 Control Algorithm Implementation

The PI controller designed through Genetic Algorithm optimization is implemented in Simulink using MATLAB Function blocks. The controller continuously monitors battery voltage and current, generates PWM signals for converters, and manages source selection logic.

5. Results and Analysis

Simulation runs for various scenarios including:

- Solar only charging (boat stationary, sunny day)
- Hydro only charging (boat moving, cloudy/night time)
- Dual mode charging (both sources available)
- Load variation (motor starting, auxiliary loads)

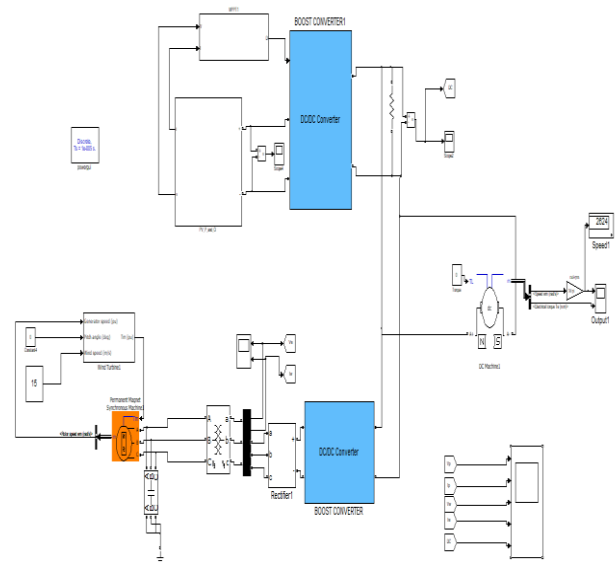
- Battery protection activation (overvoltage, undervoltage)

Waveforms of battery voltage, state of charge, source currents, and converter outputs are plotted and analyzed to verify system performance meets design specifications before proceeding to hardware implementation.

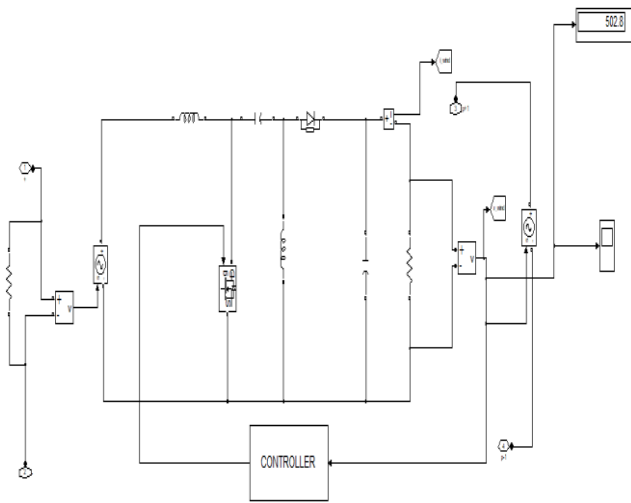
Table 3: Input & Output Parameters

Solar voltage	258V
Solar current	5.8A
Impeller voltage	240v
Impeller current	5A
Output DC voltage	500v
DC Machine speed	2624 rpm

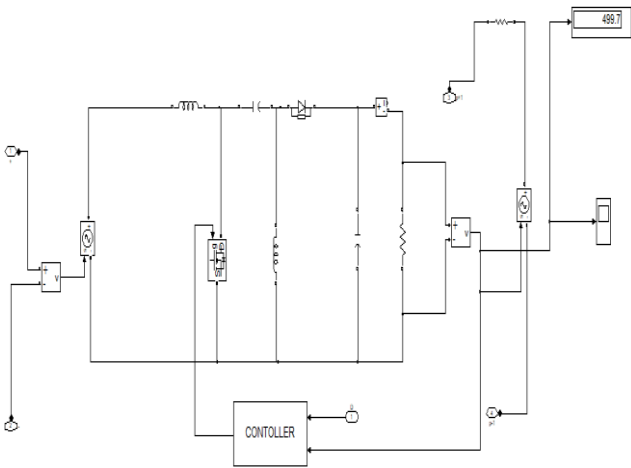
Simulation Diagram



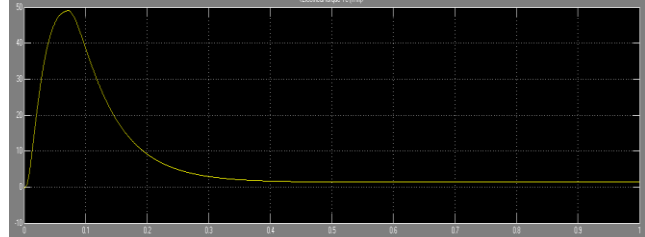
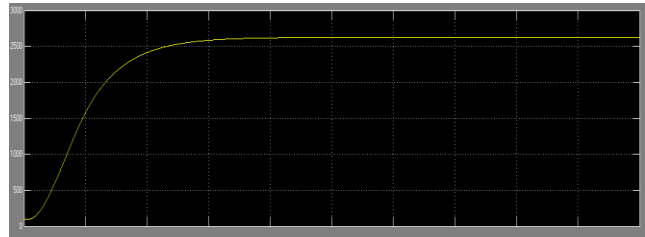
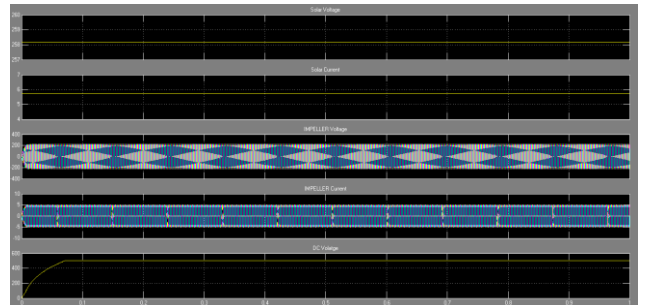
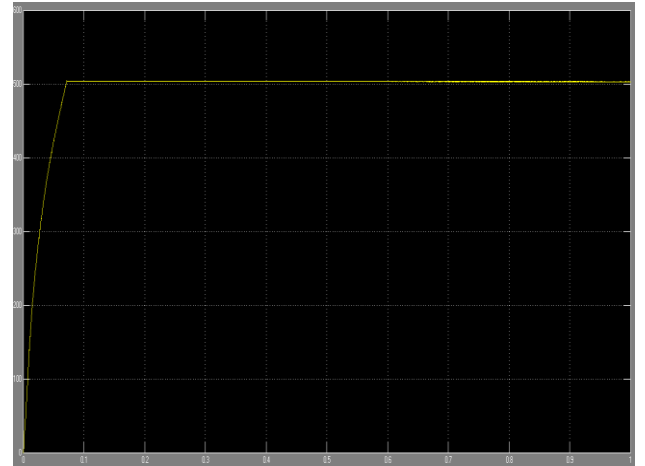
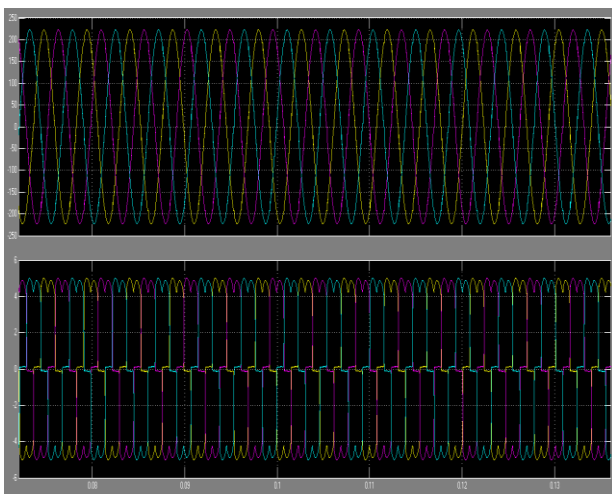
Boost converter for PV



Boost converter for wind



Simulation Result



6. Results and Discussion

The simulation of the proposed hybrid charging system was performed for three different operating modes to validate system performance under various conditions. The results are discussed below:

Mode 1: Grid Power Supply to Load (0 sec to 0.5 sec)

In this mode of operation, the load receives power directly from the conventional grid source. The hybrid renewable sources (solar PV and hydrodynamic impeller) are not connected to the load during this interval. Instead, the energy

generated from solar and hydro sources is directed entirely toward battery charging. The battery stores this harvested energy for future use. Simulation results show that from 0 to 0.5 seconds, the grid supplies stable power to the load while the battery gradually charges using available renewable energy. This mode represents typical operation when grid power is available and renewable sources are used exclusively for energy storage.

Mode 2: Renewable Sources Supply to Load (0.5 sec to 1.0 sec)

During this mode, the load is powered directly by the renewable energy sources (solar PV and hydrodynamic impeller). The grid is disconnected from the system, and the battery is neither charged nor discharged during this interval. All power generated from solar and hydro sources is fed directly to the load. Simulation results from 0.5 to 1.0 seconds demonstrate that the combined renewable sources successfully meet load demand without grid support. This mode validates the system's capability to operate independently using only harvested renewable energy when sufficient generation is available.

Mode 3: Hybrid Sources Supply to Load and Grid (After 1.0 sec)

In this mode of operation, power is supplied to both the load and the grid from hybrid sources combining renewable generation and battery storage. The system intelligently manages power flow to maintain stable voltage and current despite fluctuations in renewable generation. Simultaneously, excess energy from solar and hydro sources continues to charge the battery, maintaining its state of charge for future use. Simulation results after 1.0 second show smooth power delivery to both load and grid, with the battery acting as a buffer to absorb fluctuations and ensure uninterrupted supply. This mode demonstrates the complete hybrid system capability where renewable sources, battery

storage, and grid interface work together optimally.

7. Conclusion

The rapid growth of electric vehicle adoption has created an urgent need for efficient and sustainable charging infrastructure. Integrating renewable energy sources like solar photovoltaic systems into EV charging stations offers an environmentally friendly solution but introduces technical challenges related to power fluctuations and voltage instability. This project successfully addresses these challenges by implementing intelligent optimization techniques for DC bus voltage regulation in a PV grid-integrated EV charging station.

A smart energy management algorithm combining Maximum Power Point Tracking (MPPT) and Proportional-Integral (PI) control was developed to achieve efficient power flow regulation and stable DC bus voltage. The MPPT algorithm ensures maximum power extraction from the PV array under varying solar irradiance and temperature conditions, while the PI controller maintains voltage stability and intelligently manages battery charging and discharging cycles based on load demand and source availability.

The simulation results validate the system performance across multiple operating modes. During Mode 1 (0-0.5 sec), grid power supplies the load while renewable energy charges the battery. In Mode 2 (0.5-1.0 sec), renewable sources directly power the load without grid support. After 1.0 second in Mode 3, hybrid sources including both renewables and battery supply power to load and grid simultaneously. Throughout all modes, the DC bus voltage remains stable despite fluctuating renewable input and variable EV charging demands.

Key achievements include improved voltage regulation with minimal overshoot, enhanced power efficiency through optimized source

selection, and reliable operation under dynamic conditions. The proposed system successfully demonstrates that intelligent control strategies can effectively integrate renewable energy into EV charging infrastructure while maintaining grid stability and ensuring continuous power availability. This solution offers a sustainable pathway for reducing carbon emissions from transportation while supporting the growing electric vehicle ecosystem

8. Future Work

Future work could explore the integration of machine learning-based predictive algorithms to forecast solar generation and EV load demand, enabling even more proactive energy management. Additionally, experimental validation of the proposed control strategy using a hardware-in-the-loop testbed would be a valuable step toward real-world deployment.

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