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Article

An adaptive energy monitoring system for a hybrid power plant using renewable energy

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Abstract: The growing concern over climate change and the adverse environmental impacts of traditional thermal power plants has intensified the global focus on renewable energy sources. Renewable energy, while essential for a sustainable future, presents unique challenges due to its variability and unpredictability. To effectively harness these resources, the implementation of a Hybrid Energy System (HES) is crucial. Traditional power plants that rely on fossil fuels emit substantial amounts of greenhouse gases and toxic pollutants, along with other harmful environmental contaminants. As a result, the best solution to this problem is a power plant that uses renewable resources. Researchers strongly support hybrid power plants (HPP) because environmental factors influence the cost and availability of renewable energy in a specific area and at different times. This study focuses on creating an innovative model for a hybrid system that integrates batteries, solar, and wind energy, and manages power generation and distribution based on the cost-effectiveness of clean energy sources. This system meets load demand, charges or discharges the battery, and connects to or draws from the grid as needed. The proposed hybrid power station and its energy management system (EMS) have been modeled and simulated using the MATLAB/Simulink platform.

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1. Introduction

Researchers worldwide are diligently working to reduce greenhouse gas emissions from traditional thermal power plants. Due to climate change caused by these harmful emissions, scientific research is increasingly focused on renewable energy sources [1–7]. Renewable energy resources, which are often unpredictable, are managed through a hybrid energy system (HES) capable of meeting the estimated energy demand [8–12]. For an HES to function effectively, it requires a highly efficient energy management system (EMS) that ensures continuous power supply, optimal use of renewable resources, system stability, minimized energy generation costs, and protection from system overloads. The primary concern for utility

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companies is balancing supply and demand, which is achieved using effective EMS based on user load data [13]. Some key features of an adaptive energy monitoring system are as follows.

1. **Continuous Power Supply:** The adaptive EMS ensures a continuous and reliable power supply by seamlessly integrating various renewable energy sources, such as solar, wind, and hydroelectric power. It dynamically adjusts to fluctuations in energy production, maintaining a consistent output.
2. **Optimal Utilization of Renewable Resources:** By monitoring real-time data and predicting energy generation patterns, the system maximizes the use of available renewable resources. This reduces reliance on non-renewable backup systems and minimizes carbon emissions.
3. **System Stability:** Stability is paramount in any power system. The adaptive EMS monitors the grid's health, detecting and responding to instabilities or potential failures. It automatically adjusts energy distribution to maintain equilibrium and prevent blackouts or system overloads.
4. **Cost Efficiency:** The system reduces energy generation costs by optimizing resource allocation and minimizing waste. By predicting energy demand and adjusting supply accordingly, it ensures cost-effective operation and reduces financial strain on utility companies.
5. **Protection from System Overloads:** Overloads can cause significant damage to power systems. The adaptive EMS includes protective measures that detect overload conditions and redistribute or shed loads to prevent system damage, ensuring longevity and reliability of the infrastructure.
6. **User Load Data Utilization:** Effective energy management relies on accurate user load data. The EMS collects and analyzes this data to predict demand patterns and adjust supply in real-time. This balance between supply and demand is critical for maintaining system efficiency and meeting consumer needs.

Numerous studies have been conducted in relation to EMS for HES based on renewable resources. Grid-supported microgrids are established using an EMS depending on the internet, which lowers the cost of the microgrid [14]. The issue of power mismatch has been addressed by applying the demand response benefit [15]. Grid-microgrid integration based on renewable energy has been achieved using a method similar to homeostatic-based control for EMS. Wang et al. [16] constructed an off-grid microgrid powered by biomass, wind, and diesel using a hierarchy technique-based EMS to enhance system efficiency and dependability. Bhattacharjee et al. [17] developed an innovative EMS based on voting, where the proposed method aids in increasing customer participation in energy supply decisions and effectively managing renewable energy irregularity. An intelligent EMS controller, essential for a grid-connected HES, has been designed to supply power for electric vehicle charging stations, thus reducing pollution [18]. To account for an average day's energy consumption in remote microgrids, Amrollahi et al. [19] devised a mixed-integer linear programming method. Kanchev et al. [20] introduced a dual EMS model for microgrids based on the new concept of consumer groups.

The present study has developed a revolutionary EMS model that integrates battery storage with renewable energy sources such as solar, wind, and biomass. Additionally, the proposed HES is connected to the grid. The suggested EMS model regulates power distribution based on renewable resource availability, satisfies load demand, manages battery charging and discharging, and determines when to inject or draw power from the grid or operate in off-grid mode as necessary. As a result, the key findings of this study include:

- The suggested EMS makes it simple to control power distribution for a hybrid energy system based on renewable resources when integration is carried out at the DC level.
- The suggested EMS's algorithm helps to effectively meet load demand, adjusting the grid's power supply, and adding or withdrawing power, one can manage the distribution of electricity.

- Intended model's storage device, a battery, exhibits affirming charging and discharging characteristics based on the amount of load requirements.

The current paper's structure has been formulated in the manner shown below: The new EMS model framework is presented in Section 2, followed by Sections 3 and 4 that describe the system and represent the outcomes, and Section 5, which concludes the current study.

2. Analytical Simulation Model

The current study includes biomass, wind, and solar power that is grid-dependent HES and was created using a unique EMS model. This proposed plan converts the voltage from wind turbines and biomass energy sources to DC and uses solar panels' DC voltage. It is common knowledge that the integration of two AC power sources presents numerous challenges in terms of voltage matching, harmonics, and frequency and other related factors. Due to the absence of harmonic, frequency, voltage mismatch, and other issues, it is quite simple to integrate renewable energy with DC in order to combine all three of the generated voltages. V_T or the combined voltage would be provided by the resulting DC voltage. Three things happen if this V_T is greater than V_{req}. Load demand is satisfied, followed by converting the voltage associated from DC to AC and selling any extra energy to the grid. The battery converter now serves as a boost converter because the battery is dead and if V_T drops below V_{req}, the consequence is that there is a voltage created in the battery and is known as V_B.

Ingenious EMS design Topology

Flowchart for the suggested EMS design is displayed in Figure 1. The suggested method for variable loads was developed by employing the electrical grid's voltage as a benchmark. This method compares the DC supply voltage, which has been generated from the renewable energy source, with the peak voltage or the grid's measured DC voltage in order to determine how much power is generated from renewable sources.

Four cases are taken into consideration based on the energy management algorithm's stated technique. In these four instances: In Case 1, all three types of energy are available: solar, biomass, and wind; in Case 2, both types of energy are available: biomass and the wind; in Case 3, both types of energy are available: solar power and biomass; and in Case 4, the only energy source is biomass.

Case 1:

$$V_T = V_{sm} + V_w + V_{bio}. \tag{1}$$

Case 2:

$$V_T = V_w + V_{bio}. \tag{2}$$

Case 3:

$$V_T = V_{sm} + V_{bio}. \tag{3}$$

Case 4:

$$V_T = V_{bio}. \tag{4}$$

Depending on scenarios 1 through 4, the EMS model uses the solar panel's increased DC voltage value as V_{sm}. Converters are used to change the wind turbine voltage from alternating mode to direct mode, and then it is measured as V_w. It is necessary to convert the voltage produced by biomass from alternating mode to direct mode, and this voltage is known as V_{bio}. Next, for calculating V_T yields the entire DC voltage. Equations (1) to (4) illustrate the scenarios that affect the value of V_T. The EMS model now determines whether V_T is larger or lower than V_{req}. The needed voltage is the peak RMS voltage of the grid. Now, if V_T exceeds V_{req}, the battery gets charged and the converter begins to function as a buck converter. In

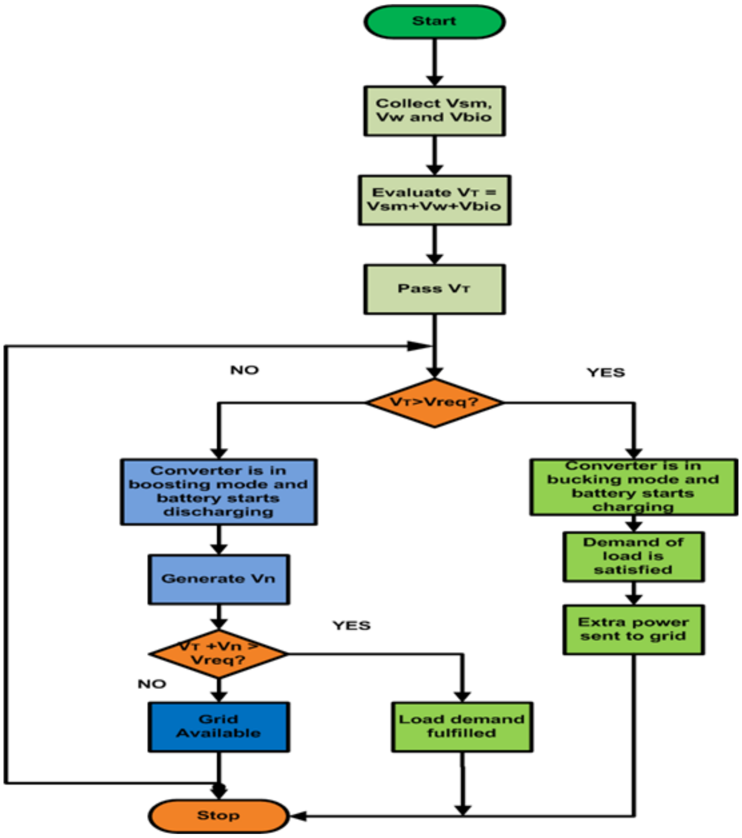

Figure 1. Proposed flowchart for a new EMS paradigm.

this scenario, the grid is provided with excess energy immediately after the requirement for delivering the load has been satisfied. The battery starts draining and produces a voltage V_B if V_T is less than V_{req}. The controller now compares if it is higher than or lesser than V_{req} by adding V_T and V_B. When the load's requirements are satisfied and the additional voltage exceeds V_{req}, electricity is pulled from the grid to provide the load.

3. Proposed Hybrid Energy System Architecture

Figure 2 shows the Simulink/MATLAB modeling for the synthesized HES. Wind, solar, and biomass are the three renewable energy resources used in the hybrid concept.

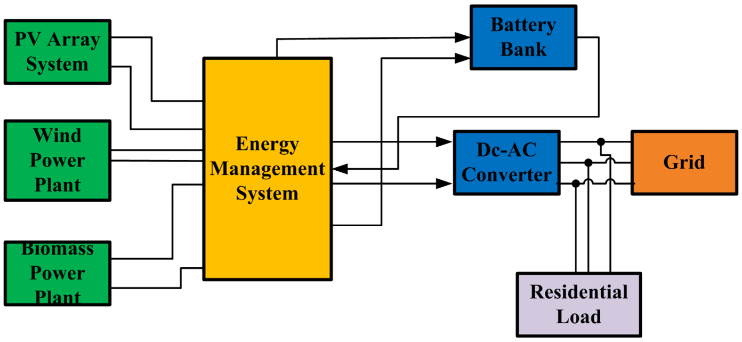

Figure 2. Model for a hybrid power system.

As seen in the previous image, the EMS controller block receives DC voltages from renewable resources. The EMS model operates in accordance with the specified algorithm. The battery in this situation serves as storage device. A converter converts the whole DC to AC voltage. Grid assistance is provided for a connected variable residential load. MPPT and a boost converter are used to connect the PV array panel. The boost converter raises the voltage, and the MPPT has been utilized to have maximum power.

3.1. Solar Photovoltaic System

The Soltech 1STH-215-P type solar panel was utilized in this installation. Table 1 displays the parameters for the panel. During the simulation, the solar irradiation of 1000 W/m^2 and the temperature of the PV panels are measured.

Following the acquisition of the PV panel's voltage and current, the boost converter increases the PV panel's voltage, and the MPPT monitors the maximum power. Duty cycle (D) represents the output of the MPPT in the simulation model. The boost converter's MOSFET receives it as a gate pulse. As a result, we can achieve ultimate voltage and current. The model uses V_{sm} to represent the enhanced voltage. The Perturb & Observe approach is used in this case to track maximum power.

Table 1. Solar Panel Parameter.

Specifications of the Panel	**Value**
Number Cells connected in series	96
Voltage from an Open Circuit (V)	64.2
I_{sc} (A)	5.96
$R_{se}(\Omega)$	0.18
$R_{sh}(\Omega)$	360
Series modules	30
Parallel modules	66

3.2. Wind Power Plant System

There are 40 wind turbines in the entire wind power facility. Each turbine has a permanent magnet synchronous generator.

Table 2. Turbine parameters.

Turbine-specific parameters	**Value**
Mechanically derived output power (W)	1.5×10^6
Base Power of Generator (VA)	$1.5 \times 10^6/0.9$
Base wind speed maximum power (pu)	0.73
Wind speed at Base level (m/s)	12
Speed of Rotation at Base (pu)	1.2
Series Modules	30
Pitch Angle (Degree)	0

3.3. System for Biomass Power Plants

The suggested method converts biomass fuel into energy by direct burning. The direct combustion method heats the water and produces steam by using biomass. After that, the steam is used to run a revolving turbine that generates energy and is coupled to a generator. The biomass power generation has a

120kW output capacity and is rated at 240 V. The resultant AC voltage is converted to DC voltage using an AC-DC converter. Using a DC-DC boost converter, the biomass power plant's voltage is raised. The biomass fuel burned per hour is 4.2 tons, and the DC voltage is denoted by the symbol V_{bio}.

3.4. Battery Storage System

The NOT operand acts as a buck converter during the battery charging condition and as a boost converter during the battery discharging condition. Everything depends on the current coming from the controller. Lithium-Ion battery was employed in the creation of this model. Lithium-Ion batteries are fairly affordable and have a very long lifespan. The fact that this form of battery harms society the least is what matters most. The battery parameters employed in the current experiment are shown in Table 3. Table 4 displays the battery's discharge characteristics.

Table 3. Battery Parameters.

Parameters	Value
Type of Battery	Lithium-Ion
Rated Voltage (V)	200
Nominal Capacity (Ah)	10
Minimum SOC	20%
Maximum SOC	100%

Table 4. Battery Discharge Property.

Property	Value
Maximum Current Capacity (Ah)	10
Voltage at cut-off level	150
Voltage during fully charged	232.7974
Rated Discharge Current (A)	4.3478
Battery Resistance (Ω)	9.0435
Capacity (Ah)	0.2

Intelligent Control Strategies for Battery Storage Systems

Battery storage systems play a pivotal role in the effectiveness of hybrid power plants using renewable energy. To ensure these systems operate optimally, intelligent control strategies are necessary. Here are some key strategies:

3.4.1. Predictive Energy Management

Utilizing advanced algorithms and machine learning, the system can predict energy production and consumption patterns. For instance, by analyzing historical data and weather forecasts, the system can anticipate periods of high energy generation from solar or wind sources and accordingly manage battery charging and discharging cycles. This ensures that excess energy generated during peak production times is stored efficiently and used when production drops.

3.4.2. Dynamic Load Shifting

Dynamic load shifting involves adjusting the energy supply to different loads based on real-time demand and battery storage levels. This strategy helps in balancing the grid and avoiding peak load stresses.

3.4.3. State of Charge (SoC) Management

Maintaining an optimal State of Charge (SoC) is crucial for prolonging battery life and ensuring reliability. Intelligent EMS monitors the SoC in real-time and makes decisions to prevent deep discharges and overcharging. The system might set a threshold to keep the battery SoC between 20% and 80%. If the SoC approaches 80%, the EMS can divert excess energy to other uses or reduce the charging rate. If the SoC nears 20%, it can prioritize charging the battery over other less critical uses.

3.4.4. Peak Shaving and Load Leveling

These strategies involve using stored energy to reduce demand during peak usage times (peak shaving) and maintaining a consistent load on the power generation system (load leveling). By discharging batteries during peak demand, the system reduces strain on the grid and avoids high energy costs. During a hot summer day, energy demand peaks in the afternoon due to air conditioning use. The EMS can discharge the batteries during this time to lower the peak load and recharge them during the night when demand and electricity prices are lower.

3.4.5. Frequency Regulation

Battery storage systems can also be used for frequency regulation, maintaining the balance between supply and demand in the grid. When there are discrepancies, the EMS can quickly inject or absorb power to stabilize the frequency.

3.4.6. Integration with Renewable Energy Sources

An intelligent EMS ensures seamless integration of various renewable energy sources with battery storage. By dynamically switching between solar, wind, and battery power, the system can maintain a steady energy supply regardless of fluctuations in renewable energy generation. Intelligent control strategies for battery storage systems are essential for maximizing the efficiency and reliability of hybrid power plants using renewable energy. By employing predictive energy management, dynamic load shifting, SoC management, peak shaving, frequency regulation, and seamless integration with renewable sources, these systems ensure optimal performance and contribute significantly to a sustainable energy future. These strategies not only enhance the operational efficiency of hybrid power plants but also pave the way for more resilient and adaptive energy infrastructures.

3.5. Converter from DC to AC

The PWM generator generates the gate impulse for the converter. The entire system must be switched to AC because the grid and residential load are both always in AC. The waves in this case have been filtered using an LC filter. In this instance, a transformer is also employed to get 440V step-down voltage.

3.6. Energy Management System (EMS)

The hybrid system's heart beats through the EMS. It frequently decides how electricity will move and how resources will be treated in a hybrid system. The more accurate the EMS model is, the more effectively energy can be controlled. Any extra power may be sent to the grid if the system's energy is properly managed. The energy management system is depicted in Figure 3.

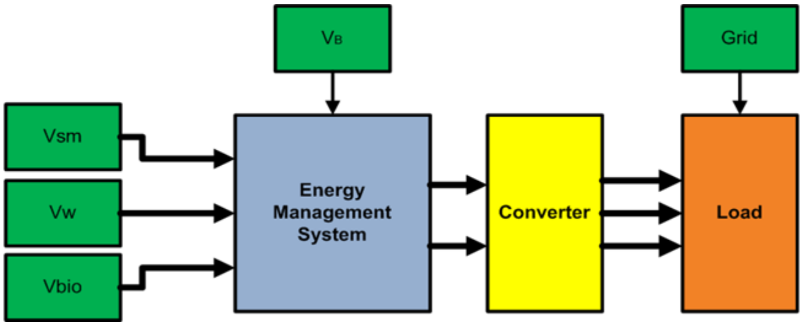

Figure 3. Model of an Energy Management System.

4. Design Algorithm to Optimize the Performance of a Hybrid Power Plant

Optimizing the performance of a hybrid power plant that integrates renewable energy sources involves a multi-step algorithmic approach. This design algorithm ensures efficient energy generation, storage, and distribution while maintaining system stability and minimizing costs.

4.1. Data Collection and Initialization

4.1.1. Collect Data

- Gather historical data on weather, solar irradiance, wind speed, and energy consumption patterns.
- Acquire real-time data from sensors monitoring renewable energy sources, battery storage systems, and load demand.

4.1.2. Initialize Parameters

- Define system parameters such as battery capacity, maximum and minimum State of Charge (SoC), generation capacities of solar panels and wind turbines, and load demand profiles.
- Set initial values for prediction models and control thresholds.

4.2. Prediction Models

4.2.1. Weather Prediction

- Use machine learning models to predict short-term and long-term weather conditions, including solar irradiance and wind speed.
- Update predictions periodically based on real-time data.

4.2.2. Energy Demand Forecasting

- Implement algorithms to forecast energy demand based on historical consumption patterns and real-time user load data.
- Adjust predictions dynamically to reflect changes in usage behavior.

4.3. Energy Generation and Storage Optimization

4.3.1. Renewable Energy Production Estimation

- Calculate the expected energy generation from solar and wind sources using predicted weather data.
- Adjust for efficiency losses and equipment performance degradation.

4.3.2. Battery Management

- Implement SoC management algorithms to maintain optimal battery charge levels, avoiding deep discharge and overcharging.
- Prioritize charging during periods of high renewable energy production and discharging during peak demand periods.

4.3.3. Load Shifting and Demand Response

- Use dynamic load shifting strategies to balance supply and demand.
- Implement demand response programs to reduce or shift energy usage during peak times.

4.4. Real-Time Control and Optimization

4.4.1. Energy Dispatching

- Develop a real-time energy dispatching algorithm to allocate power from renewable sources, batteries, and backup generators.
- Ensure the dispatching logic minimizes cost and maximizes renewable energy usage.

4.4.2. System Stability Management

- Monitor grid stability parameters such as voltage and frequency.
- Implement control strategies to inject or absorb power from the battery storage to maintain stability.

4.4.3. Peak Shaving and Load Leveling

- Utilize battery storage to shave peaks in energy demand and level loads over time.
- Ensure the battery is adequately charged to handle expected peaks based on demand forecasts.

4.5. Cost Optimization

4.5.1. Cost Function Definition

- Define a cost function that considers factors such as energy production costs, battery degradation costs, and grid electricity prices.
- Incorporate penalties for deviations from renewable energy targets and system instability.

4.5.2. Optimization Algorithm

- Implement optimization algorithms (e.g., linear programming, genetic algorithms, or particle swarm optimization) to minimize the defined cost function.
- Adjust control parameters dynamically based on real-time data to ensure ongoing cost efficiency.

4.6. Performance Monitoring and Feedback

4.6.1. Continuous Monitoring

- Continuously monitor system performance using data from sensors and control systems.
- Track key performance indicators (KPIs) such as renewable energy usage percentage, system stability, and cost savings.

4.6.2. Feedback Loop

- Implement a feedback loop to adjust prediction models and control strategies based on observed performance.
- Use machine learning techniques to improve prediction accuracy and control efficiency over time.

5. Results

The simulation results are obtained with the following parameters:

- Biomass input - 4.2 tons/hour
- Solar irradiation - 1000 W/m^2
- AC load - 40 kW
- Wind speed - 6 m/s

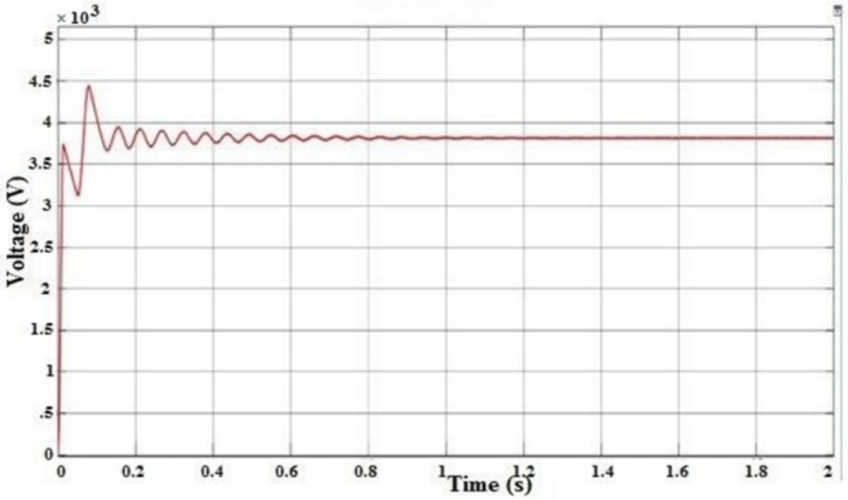

Figure 4. The output voltage of a PV panel in DC.

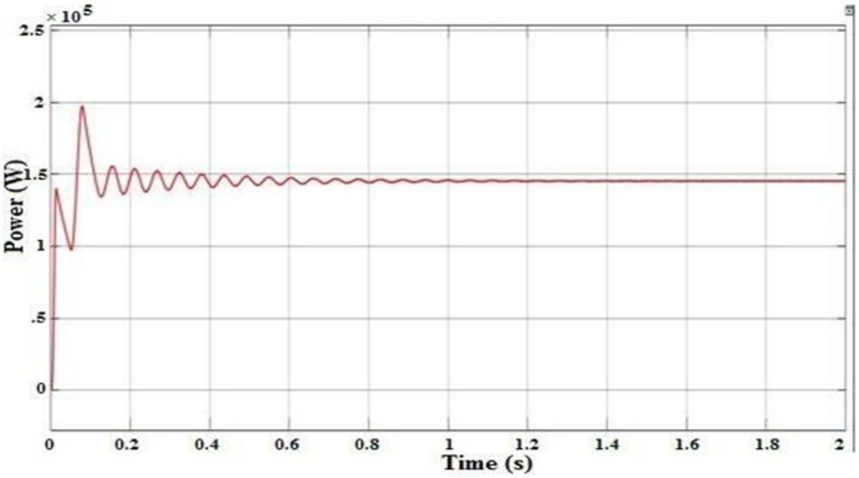

Figure 5. PV panel output power with MPPT.

The high value of solar panel output voltage is shown in figure 4. The observed DC voltage is 3814 V. The experiment's biggest peak, with a value of 4400 V, appears about 0.1 seconds in. The graph settles between 1.4 and 2 seconds at 3814 V. The highest output power of solar panel is shown in Figure 5. The DC power reading is 1.454105 W. The experiment's largest peak, at 1.9 105 W, comes 0.1 seconds in. The graph stabilizes around 1.4 seconds and stays there till 2 seconds. Figure 6 shows the 40 wind turbine output voltages when propelled by the wind. Each wind turbine will have a DC voltage of 1204.25-2204 volts, or 48170-volts. The graph climbs till it attains 2 seconds after starting at 0 seconds. Figure 7 displays the DC wind energy produced by 40 wind turbines. The graph climbs till it gets to 2 seconds after starting at 0 seconds. For a combined output of 2.49105 W electricity, each wind turbine generates 6.225 kW.

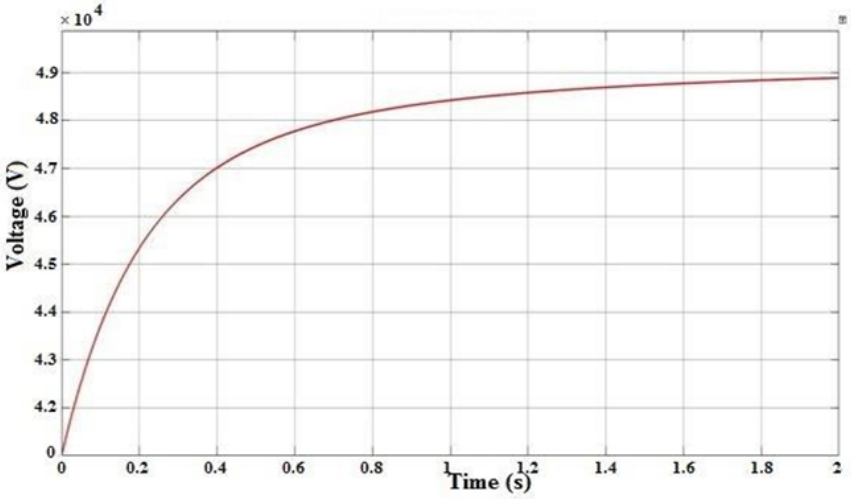

Figure 6. Output voltage of wind power plant.

Figure 7. DC output power from wind system.

The biomass power plant output voltage is shown in Figure 8. 598.3 V is found to be the DC voltage. The greatest peak, with a value of 600 V, occurs at 0.01 seconds into the simulation's lifetime. The graph levels off between 1.2 and 2 seconds at 598.3 V. The generation of DC electricity by the biomass power plant is shown in Figure 9. 5.27 105 W is discovered to be the DC power. The y-axis value for the graph, which corresponds to 2 seconds, is 5.27105 W. The graph first rises from 0 seconds and then rests for 1.2 seconds.

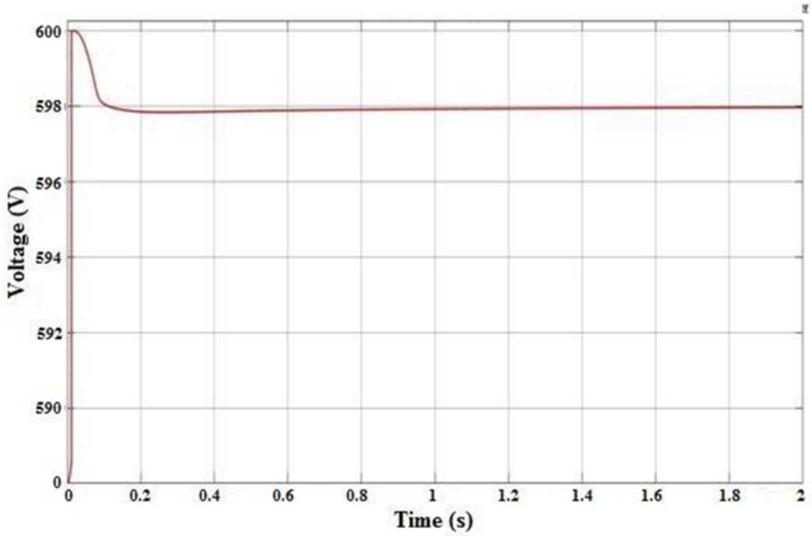

Figure 8. Output voltage of biomass plant.

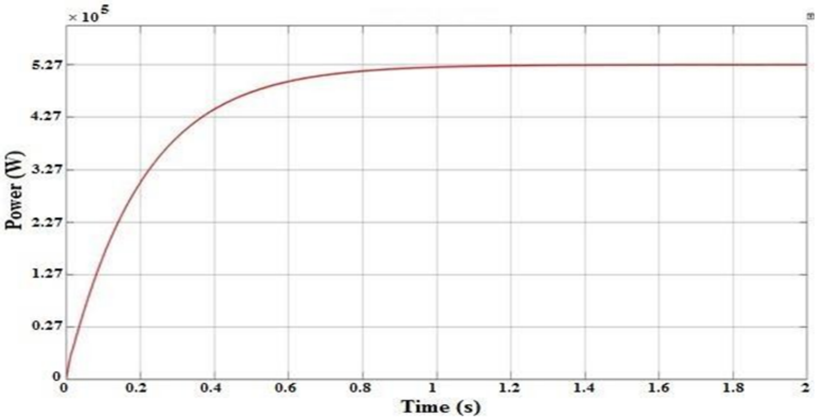

Figure 9. Biomass power plant output power in DC.

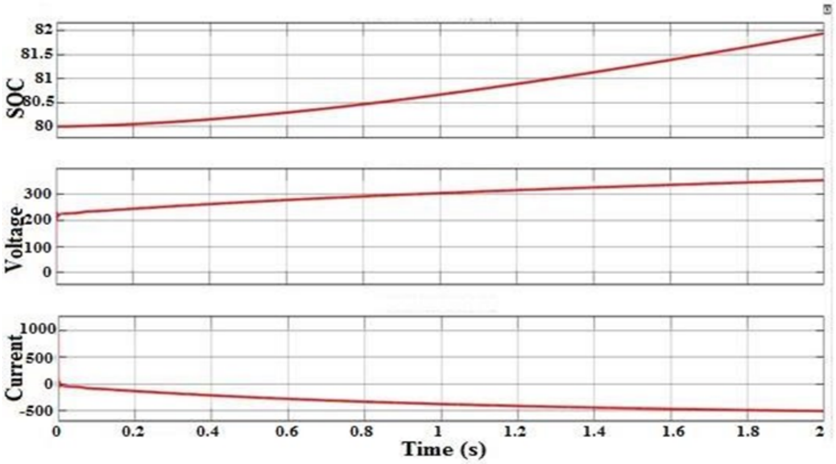

Figure 10. Graphical representation of voltage, current and SOC of battery with time.

Figure 10 shows the evolution of SOC, voltage, and current of the battery. The SOC of the battery at 2 seconds is 81.9%, as per the simulation results. Every two seconds, the battery's 350 V voltage causes a current to flow in the opposite way. It clarifies that the battery has been charged. The evolution of the grid's active and reactive power over time is shown in Figure 11. According to simulation findings, more than 175 kW of power is sent back to the grid with 0.85 lagging power factor after fulfilling load requirements. This demonstrates how well-designed the grid-dependent renewable energies are.

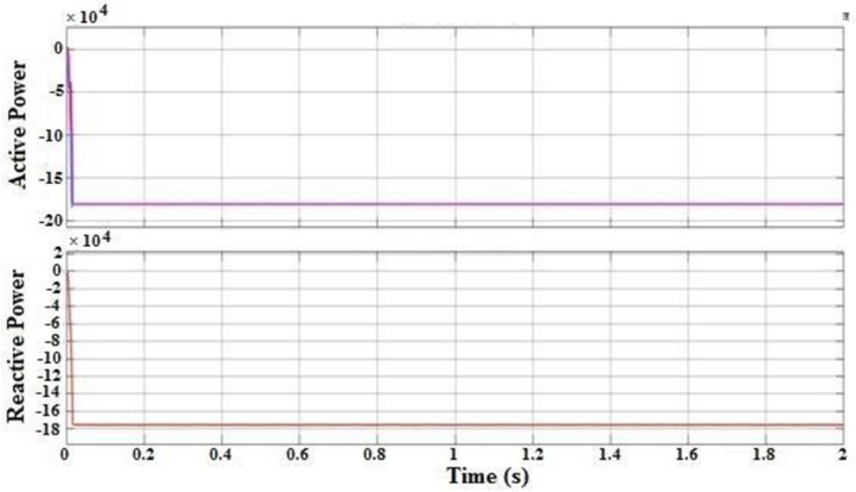

Figure 11. Time-dependent changes in the grid's active and reactive power.

6. Conclusions

The design algorithm for optimizing a hybrid power plant using renewable energy sources involves data-driven prediction, real-time control, and continuous optimization. By efficiently managing energy generation, storage, and distribution, this algorithm ensures system reliability, cost efficiency, and maximized use of renewable resources. Through ongoing monitoring and feedback, the system adapts to changing conditions, continuously improving performance.

Integrating renewable-based HES at the AC level is challenging due to issues like harmonics, frequency, and voltage matching. However, if renewable energy sources are integrated into a HES at the DC level, these problems can be resolved. A unique EMS has been developed for use with a HES that integrates renewable sources at the DC level. This EMS manages battery charging and discharging, satisfies load demands, handles power injection or consumption to/from the grid, and distributes electricity based on the cost-effectiveness of renewable resources.

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Author contributions: AKS agreed on the content of the study. AKS and GSP collected all the data for analysis. AKS agreed on the methodology. AKS and GSP completed the analysis based on the agreed steps. Results and conclusions are discussed and written together. Both authors read and approved the final manuscript.

Disclosure statement: The authors declare no conflict of interest.

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