

Optimal Energy Management and Control of a Hybrid PV/Wind System with Storage Integration

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Abstract: - This study focuses on the control and energy management of a hybrid photovoltaic (PV)/wind system incorporating grid-connected storage. The energy distribution among the different sources is regulated using a deterministic rule-based approach. The control algorithm is designed to account for all possible operating scenarios of the system. The methodology involves initializing the parameters of the various subsystems along with climatic data (temperature, solar irradiation, and wind speed) at startup. The power imbalance is then ascertained by comparing the load demand to the estimated real-time total power produced by renewable sources. The algorithm determines the proper operating mode based on this disparity. The Matlab/Simulink environment is used to model and simulate the system. The simulation results demonstrate the PV/wind system's dynamic reaction and confirm the efficacy of the control technique.

Key-Words: - Renewable energy system, Photovoltaic generator, Wind generator, Battery storage system, Control and management, State of charge (SOC).

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1 Introduction

Utilizing wind and solar resources to generate electricity has become possible thanks to advancements in wind turbine and photovoltaic production technologies. Their spontaneous behaviors are unpredictable. Nonetheless, some of them exhibit complementing patterns, such as wind speed and solar radiation, [1], [2].

A cost-effective power source that effectively utilizes both solar and wind energy is the wind/solar complementary power supply system. In addition to offering a low-cost, high-reliability solution for areas where power transmission is inconvenient, like frontier defenses and sentries, communication relay stations, farming or pasturing areas, and so forth, this system can also open a new area that addresses the energy source and environmental pollution crises.

Due to time and location constraints, it is exceedingly challenging to utilize solar and wind energy exclusively through solar or wind systems. Thus, a system that is both dependable and reliant on renewable resources is required, and a wind/solar hybrid system with battery storage can satisfy this need, [3].

The primary tool for optimizing the use of available resources remains the energy management techniques or methods for multi-source hybrid systems. The ability to handle and control the system's numerous loops is crucial for the continuation of this kind of research. This article's goal is to examine how energy generated in a multi-source hybrid system is controlled and managed.

This article's goal is to examine how energy generated in a multi-source hybrid system is controlled and managed. A photovoltaic generator, a wind generator, and a lead-acid battery-based storage system make up the multi-source system, which serves as an example of the methodology used. Matlab/Simulink is used to implement the simulation model.

2 Presentation of a Multi-Source Hybrid Renewable Energy System

The hybrid system depicted in Figure 1 is a practical application of the multi-source hybrid system under study. Photovoltaic and wind generators, along with a storage system, are renewable energy sources.

Renewable energy sources are integrated with the main DC bus using a DC/DC converter that has numerous input source interfaces. In order to capture the maximum amount of wind energy below the nominal wind speed, a variable speed control method is employed with a direct drive permanent magnet synchronous generator. This analysis takes into account changes in wind energy, solar irradiance, and load power variations. To regulate the charge/discharge (SOC) level, the acid-lead battery storage system that is coupled to the DC bus has a DC/DC converter.

The DC output of the unconventional energy is transformed into a suitable AC power source for the connected load by the inverter. The MLI approach regulates this converter to maintain the voltage across the load within reasonable bounds.

The two renewable generators and storage batteries guarantee continuous load fulfilment. The overall power generated by the renewable sources and the load's demand determines the batteries' charge and discharge states. Therefore, two thresholds (SOC_{max} and SOC_{min}) are established to regulate the storage system's operation.

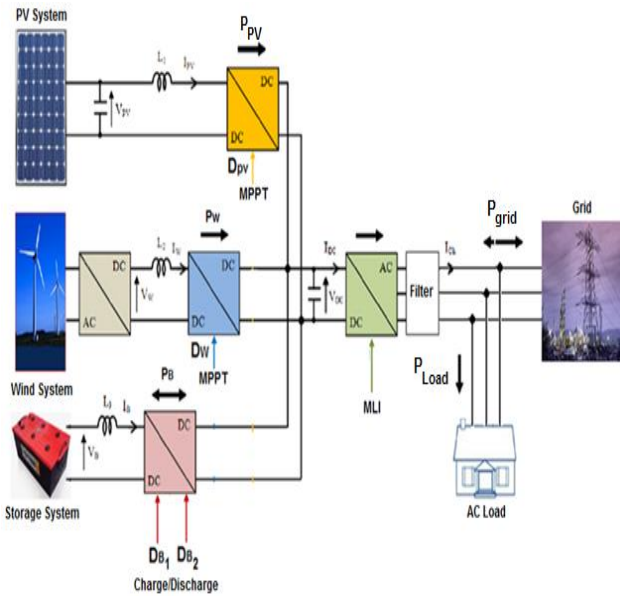


Fig. 1: Architecture of a multi-source hybrid system

Data from a day in July 2021 with a 30-minute sampling interval served as the basis for the simulation. This makes it possible to know the total power supplied by the generators, as well as the losses and battery charge level at every sampling stage.

The hybrid system is tested for different operating conditions defined by the operating depths of the storage bench ($SOC_{min} = 10\%$ and $SOC_{max} = 90\%$) and a variable load profile.

3 Characteristics of the Site

3.1 Site Description

The performance of the multi-source hybrid system depends primarily on the climatic conditions of the selected area and the load profile to be supplied.

For this study, the El Hammah region in Gabes, Tunisia, was chosen as the site. The meteorological data and load profile for this area are shown in Figure 2.

The meteorological data relevant to this project are publicly available on the website.

The coordinates of the chosen area are as follows:

- Region: El hammah
- Latitude: 33.94° N
- Longitude: 9.79° E
- Elevation: 142.14 m

3.2 Climatic Data and Load Profile

For the simulation of the hybrid system, data such as solar irradiance, temperature, and wind speed, along with a variable load profile for a summer day, were used (Figure 2).

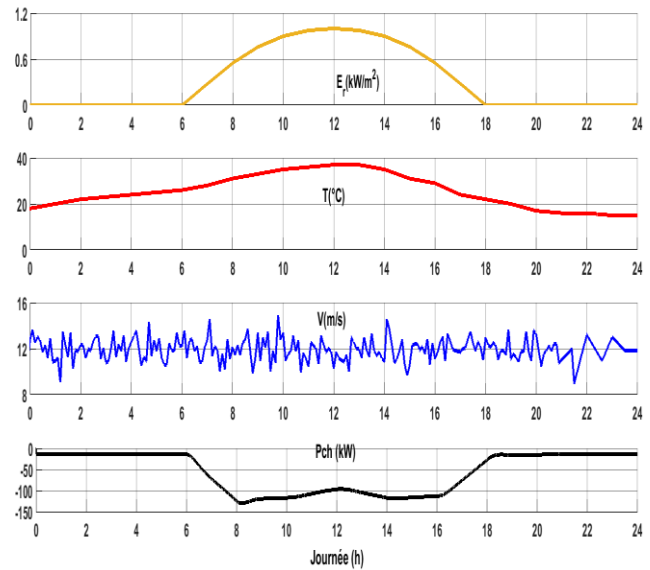


Fig. 2: Irradiation, temperature, wind speed, and load profile during a summer day (July 2021)

4 Modeling of the Hybrid System

The power generated by each energy source in the hybrid system is influenced by various factors and operating conditions.

For the photovoltaic (PV) generator, the output power is primarily determined by the ambient temperature (T_a) and solar irradiance (E_r). These two factors have a significant impact on the efficiency of

the photovoltaic panels, with higher irradiance and optimal temperatures leading to higher energy production.

In the case of the wind turbine, the power delivered is directly affected by the wind speed (V). The relationship between wind speed and the generated power is nonlinear, meaning that small changes in wind speed can result in significant variations in the power output. The efficiency of the wind generator is optimized at certain wind speeds, and deviations from this range can reduce its performance.

Regarding the storage system, the energy either supplied or stored depends on the load demand and the state of charge (SOC) of the batteries. When the load demand exceeds the available power from renewable sources, the battery storage is utilized to meet the demand. Conversely, when the generation from renewable sources surpasses the load, the excess energy is stored in the batteries. The charging and discharging processes of the storage system are controlled by predefined thresholds for the SOC to ensure the system operates within safe and efficient limits.

4.1 Photovoltaic Generator Modeling

The electrical power produced by a photovoltaic system can be expressed by the following relationship:

$$P_{pv} = P_{pv,ref} \cdot \left(\frac{E_r}{1000}\right) \cdot [1 - \gamma(T_j - 25)] \quad (1)$$

where:

- $P_{pv,ref}$ is the maximum reference power produced under standard operating conditions ($T_j = 25^\circ\text{C}$ and $E = 1000 \text{ W/m}^2$).
- E_r is the incident solar irradiation (W/m^2)
- The coefficient of variation of efficiency with respect to temperature, denoted by γ , is assumed to be constant. For silicon cells, its value typically ranges between 0.0035 and $0.0050 \text{ }^\circ\text{C}^{-1}$.
- T_j The cell junction temperature expressed (in $^\circ\text{C}$), ($T_{j,ref} = 25^\circ\text{C}$).

The photovoltaic (PV) system consists of 330 modules, organized into 66 parallel branches with 5 modules connected in series. Under standard operating conditions, the system can deliver a maximum power of 100 kW.

The typical current-voltage (I-V) and power-voltage (P-V) characteristics of the solar generator are shown in Figure 3.

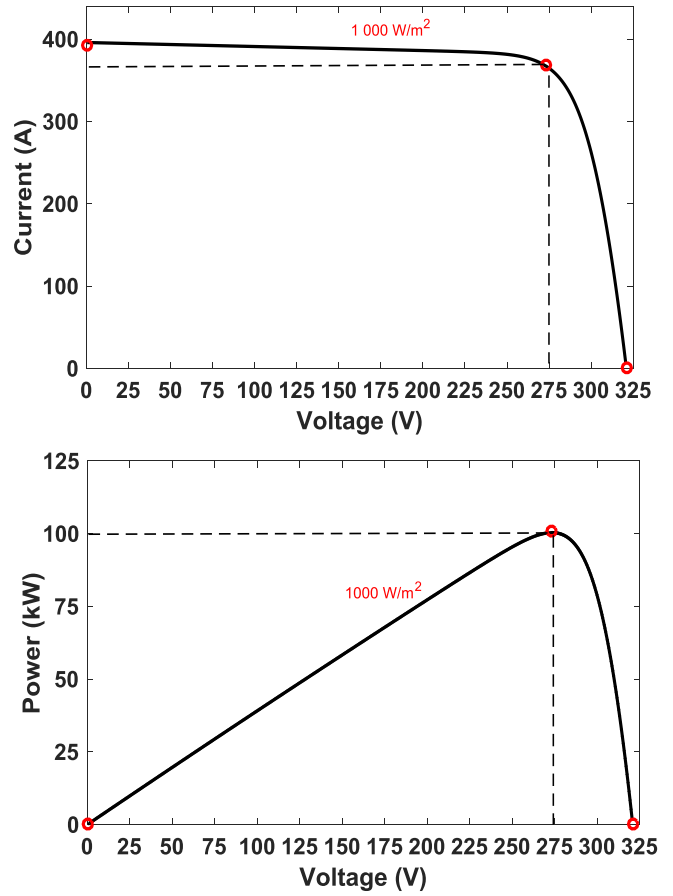


Fig. 3: Current-voltage (I-V) and Power-Voltage (P-V) characteristics of the solar generator

4.2 Wind Generator Modeling

In this study, we focus on a wind turbine system that is coupled with a permanent magnet synchronous generator (PMSG) via a shaft and a speed multiplier. The wind turbine captures kinetic energy from the wind, which is then converted into mechanical energy. This mechanical energy is transmitted through the shaft to the permanent magnet synchronous generator, where it is transformed into electrical energy. The speed multiplier is used to adjust the rotational speed of the turbine to match the optimal operational speed of the generator.

The electrical power generated by the wind turbine can be expressed using the following formula, [4], [5]:

$$P_W \begin{cases} 0 & V < V_c \text{ Or } V > V_{max} \\ P_{wn} \cdot \left(\frac{V^2 - V_d^2}{V_n^2 - V_d^2}\right) & V_c \leq V \leq V_n \\ P_{wn} & V_n \leq V \leq V_{max} \end{cases} \quad (2)$$

where:

- P_W : wind power at wind speed V ;
- P_{Wn} : the rated power of the wind generator;
- V_n : rated wind speed,
- V_d : the starting wind speed,
- V_{max} : the maximum wind speed

The wind generator provides a power of 50 kW at the rated wind speed of 12 m/s (Figure 4).

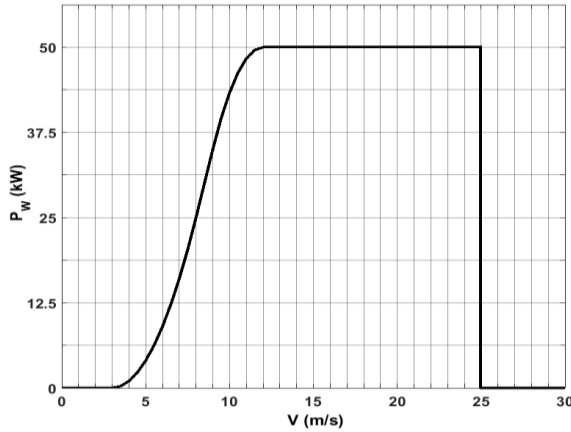


Fig. 4: Power characteristics of the wind generator

4.3 Modeling of the Battery Storage System

Among the various battery models, the one that focuses on the observation of the physicochemical phenomena during the charging and discharging processes of the storage system is particularly useful.

This model captures the dynamic behavior of the battery, taking into account factors such as internal resistance, voltage variation, and the state of charge.

To represent the behavior of the battery in the system, we use Thevenin's equivalent circuit model, which simplifies the complex internal characteristics of the battery into an easily manageable form. This model includes a voltage source that represents the open-circuit voltage of the battery and a series of resistances that account for the internal losses. Figure 5 shows the Thevenin equivalent circuit used for the battery modeling.

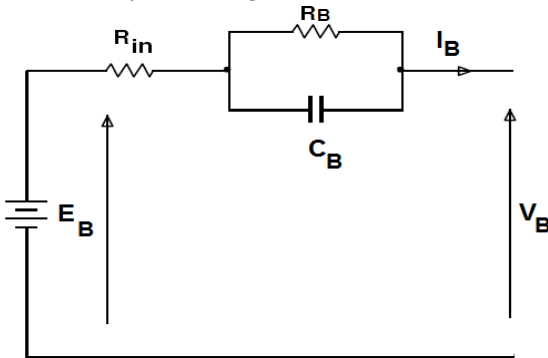


Fig. 5: Thevenin's equivalent circuit model of the battery

The capacitance equivalent, denoted as C_b , can be expressed as:

$$C_B + \frac{Q_B(kWh) \times 3600 \times 1000}{0.5(E_{Bmax}^2 - E_{Bmin}^2)} \quad (3)$$

The mathematical model of battery voltage is therefore:

$$V_B = E_B - Z_B \cdot I_B \quad (4)$$

The current, denoted by I_{Batt} represents the algebraic value of the battery's current, being positive during charging and negative during discharging.

The nominal capacity of the storage system, based on the unit capacity of a single battery, is given by equation 5.

$$Q_n = N_B \cdot Q_B \quad (5)$$

Where:

N_B : represents the total number of batteries; and Q_B is the unit of a single battery.

This model makes it possible to calculate the storage energy according to the energies; produced by the hybrid system and that required by the load. It is stipulated as follows.

- When the energy produced is greater than that required by the load; the battery energy at time (t) can be expressed by the following relationship:

$$E_{char}(t) = E_{char}(t-1) \cdot (1 - \tau_h) + \left(E_{Prod}(t) + \frac{E_{Load}(t)}{\eta_{DC/AC}} \right) \eta_B \quad (6)$$

- When the load demand exceeds the generated power, the energy stored in the batteries at time (t) can be expressed as follows:

$$E_{char}(t) = E_{char}(t-1) \cdot (1 - \tau_h) - \left(\frac{E_{Load}(t)}{\eta_{DC/AC}} - E_{Prod}(t) \right) \eta_B \quad (7)$$

Where:

- $E_{char}(t)$ and $E_{char}(t-1)$ represent the state of charge in (Wh) of the battery bank at times (t) and (t-1) respectively.
- τ_h is the hourly battery discharge rate, generally estimated at 0.2% per day for most batteries;
- $E_{prod}(t)$ and $E_{dem}(t)$, are respectively the energies produced and demanded at time t;
- $\eta_{DC/AC}$ and η_B , are respectively the efficiency of the inverter and the batteries, [6], [7].

Various techniques have been developed to control the state of charge/discharge [8], typically

based on the voltage measured at the battery terminals, which serves as the primary indicator of the battery's State of Charge (SOC). The selected battery technology supports a 35% discharge (with a minimum SOC of 10%). It achieves an energy efficiency (η_{β}) of 100% during charging and 80% during discharging.

One method for managing the SOC involves measuring and calculating the quantities of electricity flowing into and out of the battery during both charge and discharge processes, typically expressed in ampere-hours. This approach is known as coulomb counting or metric coulomb measurement.

The state of charge of batteries by the following constraints: $SOC_{min} \leq SOC \leq SOC_{max}$

where:

SOC_{max} and SOC_{min} Being the charge/discharge limits of the batteries. The state of charge of the battery at a given time depends directly on the previous state of charge, which must be known beforehand.

$$SOC(t) = SOC(t - 1) + \left(P_{Prod}(t) - \frac{P_{Load}(t)}{\eta_{DC/AC}} \right) \cdot \frac{\eta_B}{V_{Bus}} \cdot \Delta t \quad (8)$$

with:

$$P_{Prod}(t) = P_{pv}(t) \cdot \eta_{DC/DC} + P_{wind}(t) \cdot \eta_{AC/DC} \quad (9)$$

where:

Δt : The step simulation;

$P_{Prod}(t)$: Power of renewable generators; $P_{Load}(t)$: Power demanded by the load during a time instant t ;

The battery storage system has a capacity of 780 Ah - 48 V.

5 Energy Control and Management of the Hybrid System

Energy management between the various components of the hybrid system is achieved using a technique based on deterministic rules, [9], [10]. This approach is designed to account for all possible operating scenarios of the system under study.

The flowchart in Figure 6 illustrates the operational principle of the energy management strategy for our system. Initially, the parameters of the different subsystems and the climatic data (temperature, irradiation, wind) are set. Then, the total power P_{Prod} generated by the renewable sources (PV/wind) and the load demand P_{Load} are evaluated at each time step, allowing the calculation of the power difference ΔP .

$$\Delta P(t) = P_{Prod}(t) - P_{Load}(t) \quad (10)$$

- If $\Delta P=0$, the total power produced by the renewable sources matches the power required by the main load ($P_{Prod}=P_{Load}$). As a result, the state of charge of the batteries remains constant (battery in idle mode). The buck-boost converter (between the batteries and the DC bus) operates in offline mode.

- If $\Delta P>0$ the total power produced exceeds the load demand. In this case, there is surplus energy available to supply the load and store the excess.

If the state of charge (SOC) is greater than or equal to the maximum SOC ($SOC \geq SOC_{max}$) the storage system is disconnected, and any remaining energy is fed back to the grid ($P_{Grid}>0$).

- If $\Delta P<0$, the energy produced is insufficient to meet the load demand. If the battery charge level is within the acceptable range $SOC_{min} \leq SOC \leq SOC_{max}$; the storage system is activated to compensate for the energy shortfall.

In the event that the $SOC < SOC_{min}$; the storage system is put into offline mode and the rest of the demand is taken from the network ($P_{Grid} < 0$).

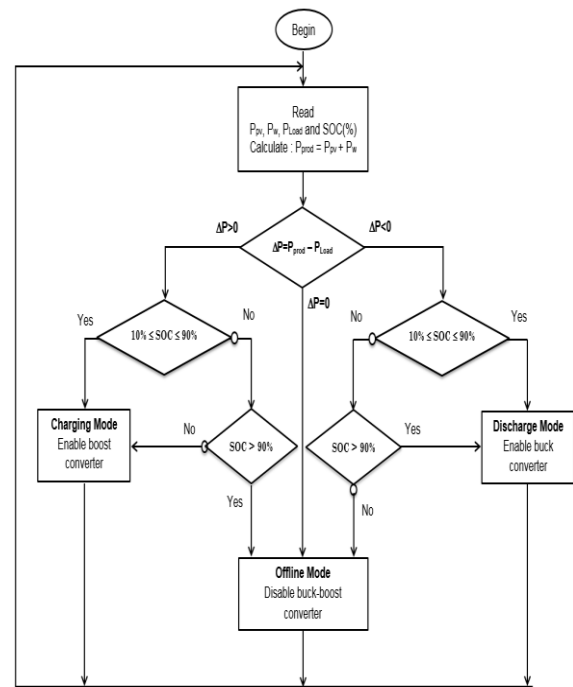


Fig. 6: Algorithm for selecting operating modes

6 Simulation Results

To evaluate the effectiveness and robustness of the proposed energy management algorithm, several operating scenarios have been considered. These scenarios aim to analyze the system's response under different conditions, including variations in renewable energy production, fluctuations in load demand, and battery charge/discharge dynamics. The following sections provide a detailed

description of these test cases and their impact on the overall performance of the hybrid system.

6.1 Clear Day, Wind Power at Rated Value and Charged Batteries ($10\% \leq \text{SOC} \leq 90\%$)

The simulation, conducted under the constraints of battery state of charge and varying load demand, has provided the following results. Figure 7, Figure 8, Figure 9 and Figure 10 illustrate the power flow, voltage variations, and battery status throughout the day.

Under these conditions, we observe that when the generated power exceeds the load demand ($P_{\text{prod}} > P_{\text{Load}}$), the excess energy is used to charge the batteries, and any remaining surplus is injected into the grid ($P_{\text{grid}} > 0$). Conversely, in periods of energy deficit ($P_{\text{prod}} < P_{\text{Load}}$), the batteries discharge to partially compensate for the shortfall, while the remaining required power is drawn from the grid ($P_{\text{grid}} < 0$).

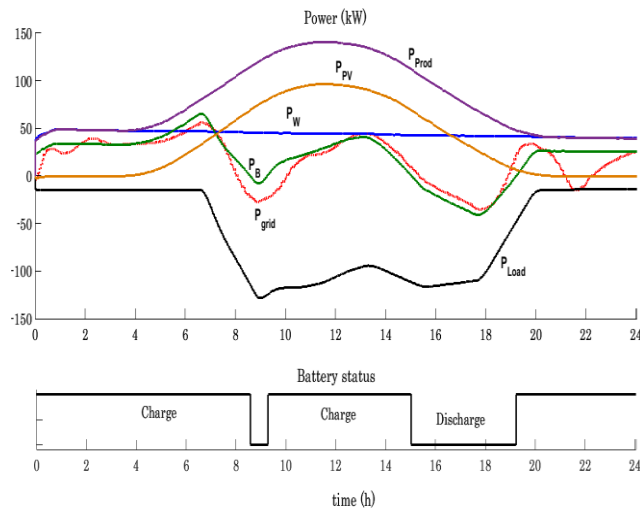


Fig. 7: Power flow and battery status during the clear day

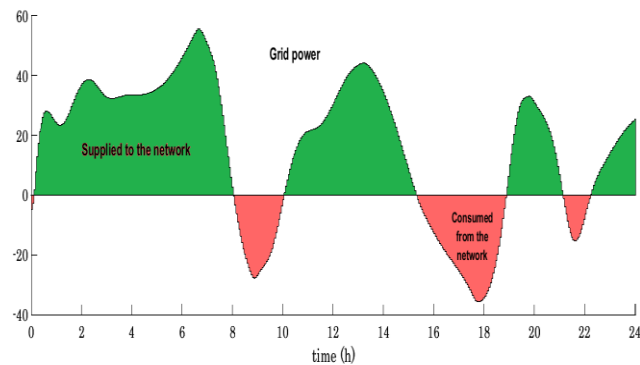


Fig. 8: Power supplied and consumed from the grid

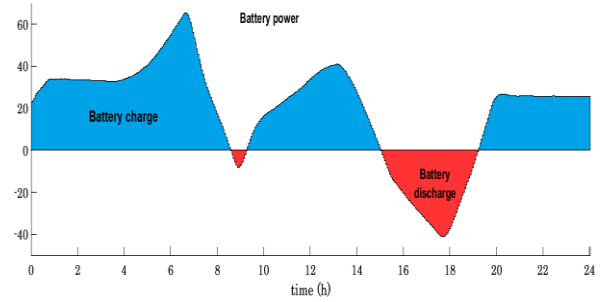


Fig. 9: Variation of battery energy during the day

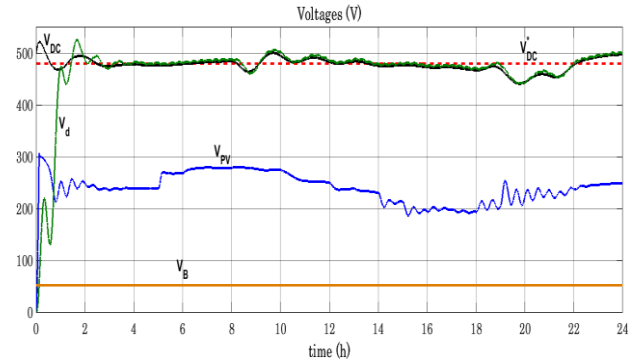


Fig. 10: Variations of different voltages during the day

6.2 Normal State of Main Sources and SOC < 10%

For this scenario, the battery charge level is below ($\text{SOC} < \text{SOC}_{\text{min}}$). Surplus energy is stored in the batteries (charging mode) and the rest is returned to the grid. In the event of an energy deficit ($P_{\text{prod}} < P_{\text{Load}}$), the batteries are unable to fill the gap and are put into disconnected mode. The power grid takes the load to meet the demand ($P_{\text{grid}} < 0$). Figure 11, Figure 12 and Figure 13 show the power flow and battery status during the day.

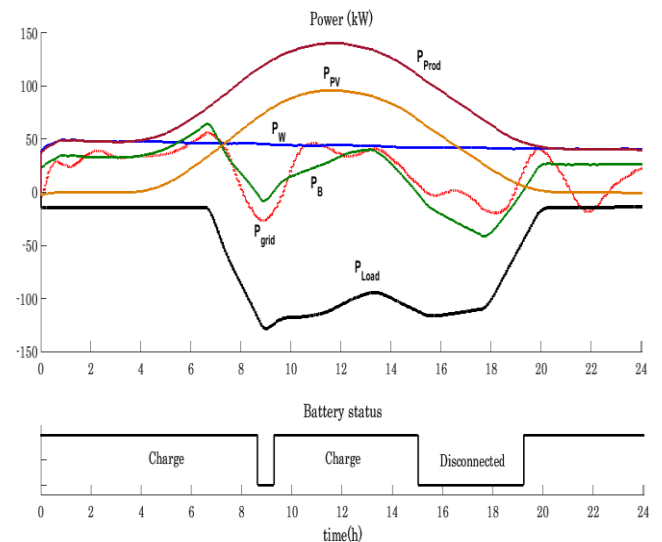


Fig. 11: Power flow and battery status during the clear day

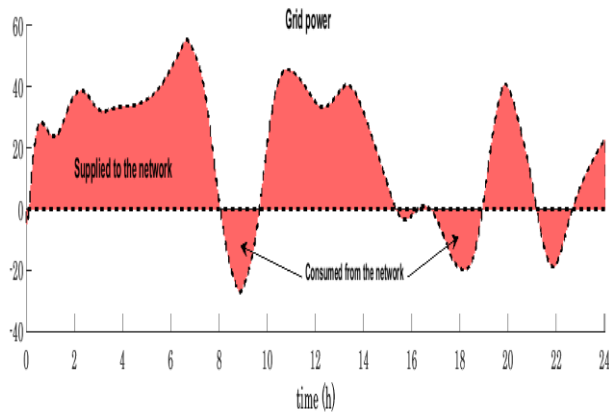


Fig. 12: Power supplied and consumed from the grid

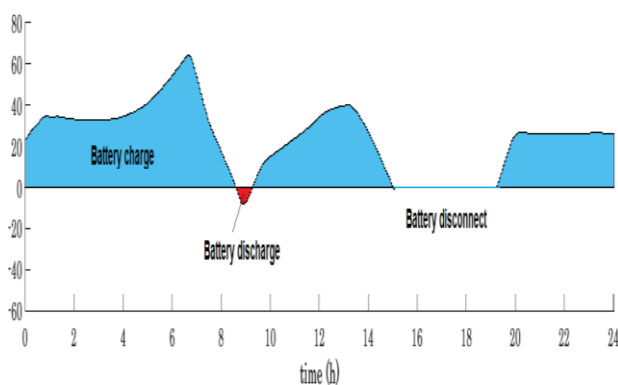


Fig. 13: Evolution of battery energy during the day

7 Conclusion

In this study, we developed and simulated a control strategy for a grid-connected multi-source hybrid system, integrating a photovoltaic generator, a wind turbine, and a battery storage system. The proposed approach focuses on designing an algorithm to efficiently manage energy flows within the system while ensuring the satisfaction of load demand and maintaining the battery's state of charge within safe operational limits.

The energy management algorithm is designed to optimize the use of available renewable energy sources, ensuring continuity of supply even in cases of fluctuating or insufficient renewable generation. Additionally, it protects the battery system against overcharging and deep discharges, enhancing its longevity and reliability.

The algorithm was validated through a one-day simulation with a variable load profile. The obtained results demonstrate its effectiveness in balancing power production, storage, and consumption, confirming its ability to ensure efficient energy management.

Future improvements could involve integrating advanced artificial intelligence techniques, such as

neural networks, fuzzy logic, or genetic algorithms, to further enhance the system's adaptability and optimization capabilities.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the authors used QuillBot in order to improve the language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Laila Bouaziz: Conceptualized the article, formulated the problem, modeled the hybrid system, conducted Matlab/Simulink simulations and wrote the main sections, including the introduction, methodology, and results.
- Mehdi Dhaoui: Co-supervisor, provided guidance on the energy management algorithm, reviewed and validated the methodology and results.
- Mouna Ben Hamed: Supervisor, provided overall guidance on the research direction, reviewed and validated the manuscript, including simulations and interpretation of results.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.

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