Energy Management of PV-Batteries System for a Rural Micro-Grid Application in Guinea

Mohamed Lamine Touré[1,2], Mamadou-Baïlo Camara[1], Claude Bertin Nzoundja Fapi[3], Alireza Payman[1] and Brayima Dakyo[1]

[1] GREAH Laboratory, University of Le Havre Normandie, 75 Rue Bellot, 76600 Le Havre, France
[2] Université Gamal Abdel Nasser Conakry, Guinea
[3] LIED Laboratory, UMR 8236 CNRS, Université Paris Cité, 35 rue Hélène Brion, 75006 Paris, France
e-mail: mohamed-lamine.toure@etu.univ-lehavre.fr; mamadou-bailo.camara@univ-lehavre.fr;
claude-bertin.nzoundja-fapi@u-paris.fr; alireza.payman@univ-lehavre.fr; brayima.dakyo@univ-lehavre.fr

***Abstract*—Integration of solar energy in stand-alone micro-grid applications is an attractive solution for improving access to electrification in remote rural areas and reducing dependence on the main power grid. This paper proposes a control strategy to manage the energy of a hybrid system comprising photovoltaic (PV) solar panels and energy storage batteries. The aim is to maximize the use of PV solar energy by using a PV voltage model that considers the variations of the series resistance as a function of solar irradiance and operating temperature. This ensures optimum operations of the micro-grid and improves energy efficiency. The strategy adopted is based on a dual approach that combines a maximum power point tracking algorithm with incremental conductance to extract the maximum power from the solar panels, and an energy management system based on rules control. The proportional-integral controller regulates the batteries power flow to maintain a stable DC-bus voltage within the micro-grid. System performance is evaluated in the Matlab/Simulink software environment for different load profiles and sunlight conditions. The simulations results show a significant efficiency of the control system with PVs power fluctuations mitigating by the batteries to reduce the current stress for the load.**

Keywords—Photovoltaic; ernergy management system; energy storage batteries; DC-bus voltage regulation; micro-grids.

I. INTRODUCTION

The global climate crisis and the gradual depletion of fossil fuels are making the development of sustainable energy solutions an imperative. The integration of renewable energy sources into stand-alone micro-grid systems, in particular, offers a promising alternative for reducing greenhouse gas emissions and increasing energy independence. Among these sources, solar photovoltaic (PV) energy is abundant in West-Africa (Guinea), clean and increasingly accessible thanks to the falling cost of conversion technologies.

However, optimal operation of a PV source remains complex due to its variable and non-linear nature. Solar irradiance and temperature have a strong influence on the power generated, requiring dynamic Maximum Power Point Tracking (MPPT) to ensure optimum energy yield. Several MPPT techniques have been developed, including perturb and observe (P&O), incremental conductance (InC) and adaptive step methods, such as those explored in [1], [2], [3]. The InC algorithm, in particular, is recognized for its ability to better converge to the maximum power point under conditions of high solar radiation variability.

Furthermore, energy management based PVs and batteries Energy Storage Systems (ESS) requires an Energy Management Strategy (EMS) capable of making the fast decisions to direct energy to Electric Vehicles (EVs) or to the batteries. Several studies have proposed EMS based on fuzzy rules, decision logic or hierarchical approaches. For example, Swetha et al. [4] proposes a strategy based on a centralized model for EV applications in a micro-grid environment. Oukkacha et al. [5] present an energy management method for electric vehicles based on frequency sharing between a fuel cell, lithium-ion batteries and the supercapacitors, each connected via DC-DC converters. Badawy and Sozer [6] developed and implemented an Energy Management Strategy Control (EMSC) for renewable source with the batteries micro-grid system. Baqar et al. [7] conducted a comparison of various EMSC. They are done on a hybrid system based on fuel cell, supercapacitors and batteries, highlighting the importance of effective coordination to extend the batteries life. Similarly, Bonkile and Ramadesigan. [8] proposed a solution for autonomously managing a PV-batteries hybrid system for electrical energy storage by minimizing overload constraints using the Runge-Kutta method with high-stability time steps.

Concerning the DC-bus voltage regulation, a crucial element in on-board or stationary vehicle architectures, the use of conventional controllers (PI, PID) is still common to guarantee system voltage stability [9], [10]. Yaqoob et al. [11] proposes a power EMS based on platitude control for a stand-alone photovoltaic-battery hybrid system, aimed at stabilizing the DC-bus voltage and optimizing power sharing between sources. Similarly, an EMSC for a DC micro-grid integrating a PV module, batteries and the load, aimed at optimizing energy flow while preserving battery's life, is proposed in [12]. Benzaouia et al. [13] experimentally evaluated a control strategy for a PV/battery system dedicated to water pumping applications using neural network for maximum power extraction on the PV side and fuzzy logic on the battery side to maintain the balance between supply and demand.

Despite these advances, few studies have combined an InC-type MPPT strategy with a PI control dedicated to DC-bus voltage regulation, applied to a PV/battery architecture oriented towards stand-alone micro-grids with emphasis on the voltage model of the PV system with variable series resistance, all set under realistic weather conditions. In this work, the authors propose a PV/batteries system dedicated to stand-alone micro-grid applications. Proposed EMS includes InC MPPT algorithm, which ensures the maximum power extraction of PV energy under variable irradiance and the PV series resistance. The MPPT is assisted by two PI controllers, one ensuring stability of the DC-bus voltage at 1000V through efficient control of the batteries charge/discharge via a bidirectional DC-DC converter, and the second, via a unidirectional DC-DC Boost converter, transferring power from the PV system to the DC-bus.

The system is simulated using Matlab/Simulink with realistic climatic profiles (irradiance and temperature based on pilot site of Dialakoro in Guinea). The aim is to analyze the system's performance in a variety of production and consumption scenarios, focusing on DC-bus voltage stability, battery safety and overall energy conversion efficiency. The results obtained demonstrate efficient regulation, optimized use of solar energy, and optimal batteries utilization, making this approach particularly suitable for stand-alone micro-grid solutions.

Following this introduction, the paper is organized as follows: Section 2 describes the micro-grid architecture, focusing on the modeling of PV sources and batteries storage systems. Section 3 is devoted to energy management strategies; it first introduces the principle of MPPT control, then details the energy management strategy. Section 4 presents the simulation results and proposes an in-depth analysis. Finally, Section 5 concludes this study.

II. DESCRIPTION OF MICRO-GRID

Figure 1 illustrates the overall architecture of the hybrid system studied, which integrates a variable series resistance PV source, a battery storage system and a load represented by a home. The PV generator is connected to a boost converter, driven by a control signal (*Duty Cycle PV*) from the Maximum Power Point Tracking (MPPT) control strategy. The latter applies a MPPT algorithm to optimize the power extracted from the PV field, dynamically adapting the operating point. The storage system consists of the batteries, connected to the DC-bus via a bidirectional DC-DC converter, controlled by a dual signal (*Duty Cycle BatBus*) generated by the energy management system. This converter enables the batteries to be charged when PV production is in excess, and discharged to feed the load when solar production is low. The micro-grid, as the main load, is supplied by the DC-bus, whose voltage regulation is ensured by the coordinated power management through the two converters. This architecture enables intelligent, adaptive energy management, making it possible to integrate the PV system into a micro-grid, contributing to energy flexibility and reducing dependence on the large interconnected grid.

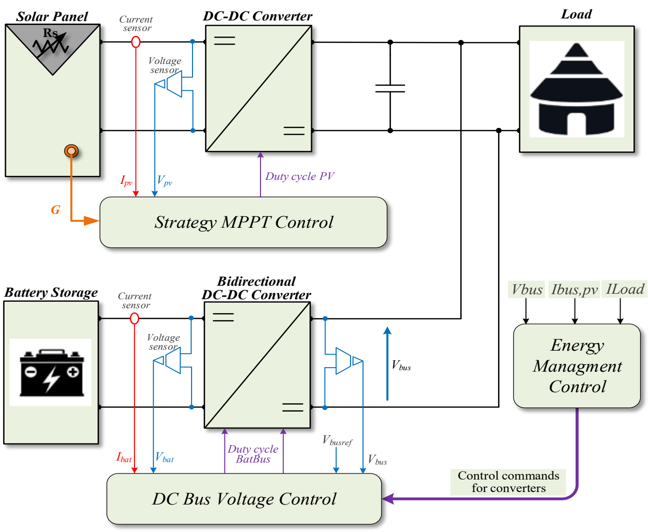

Figure 1. Proposed power system topoloy.

A. Modeling of Solar PV

Several mathematical models of PV panels have been developed with the aim of accurately representing their electrical properties and operation, which derive directly from the physical structure of PV cells as in [14], [15]. In this study, the PV model used is based on the methods described in [2]. The PV voltage model with variable series resistance is connected directly to the DC-bus via a boost converter, thus guaranteeing power transfer from the PV string to the DC-bus.

Table 1 lists the main technical characteristics of the PV module and DC-DC boost converter. In addition, the voltage-current (I-V) properties of the PV panel, and the links with power output, can be explained using (1), which summarizes the electrostatic behavior of the module under standard irradiance and temperature conditions.

$$\begin{cases} V_{pv} = \alpha \cdot \dfrac{n \cdot k \cdot T}{q} \cdot \ln\left(\dfrac{I_{ph} - \frac{I_{pv}}{N_{p,ch}} \cdot k_{\lim i}}{N_{sc} \cdot I_o} \cdot \beta + 1 \right) - I_{pv} \cdot R_s \cdot \lambda \\ \alpha = N_{s,ch} \cdot N_{sc} \\ \beta = \left(\dfrac{T}{T_{ref}} \right)^3 \cdot \exp\left(\dfrac{q \cdot E_g \left(\frac{1}{T_{ref}} - \frac{1}{T} \right)}{n \cdot k} \right) \\ \lambda = \dfrac{N_{s,ch} \cdot N_{sc} \cdot k_{\lim v}}{N_{p,ch}} \\ k_{\lim i} = \dfrac{I_{sc} - I_{mp}}{I_{mp}} \\ k_{\lim v} = \dfrac{V_{oc} - V_{mp}}{V_{mp}} \end{cases} \quad (1)$$

where I_{pv}, V_{pv}, I_o and I_{ph} represent PV current, voltage, saturation current and photocurrent, respectively. The series and parallel resistances are R_p and R_s. N_s and N_p are the total number of solar modules connected in series and parallel respectively. T is the PV surface temperature. n, E_g and k are the ideality factor, gap energy and Boltzmann constant, respectively.

TABLE I. CHARACTERISTICS OF PV PANEL AND BOOST CONVERTER

Electrical Parameters	**Values**
Solar PV source	
P_{mpp}: Maximum power	*345 W*
I_{mpp} : Maximum Current	*9.05 A*
I_{sc}: Short-circuit current	*9.52 A*
V_{mpp}: Maximum voltage	*38.14 V*
V_{oc}: Open-circuit Voltage	*46.52 V*
k_{sc}: Temperature coefficient of current	+0.049 *% /°C*
k_{oc}: Temperature coefficient of voltage	-0.315 *% /°C*
N_{sc}: Series cells	72
$N_{s,ch}$: Number of modules in series in a PV string	7
$N_{p,ch}$: Number of parallel strings in a PV string	80
DC-Dc boost converter	
C_{out}: Capacitor	*3300 µF*
L: Inductance	1 *mH*
f: Switching frequency	10 *kHz*

B. Behavior modeling of the batteries

The batteries are high energy density, quick dynamic response, and low rate of self-discharge make it a promising technology for storing renewable energy in hybrid systems. As depicted in Figure 1, the batteries are connected to the DC-bus via a bidirectional DC-DC converter, enabling efficient DC power supply to the load. The considered model of the batteries is presented by (2) [16], [17].

$$V_{bat} = E_0 - K \cdot \frac{Q}{Q - i_t} - R_b \cdot i + A_b \cdot e^{(-B \cdot i_t)} - K \cdot \frac{Q}{Q - i_t} \cdot i_f \quad (2)$$

In (2), the open-circuit voltage is denoted by E_0. Q is the capacity (Ah) of a typical battery. i_t is the battery's current charge (Ah). The polarization constant is denoted by K. The exponential zone amplitude (in V) is shown by A_b. B represents the exponential zonetime constant inverse in the exponential

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zone (Ah^{-1}). The internal resistance (in Ω) is denoted by R_b. The battery's current is denoted by i, and the filtered current (in A) by i_f.

The battery design was modeled using simulation based on the technical specifications listed in Table 2, which also includes the parameters of the bidirectional DC-DC converter. The model describing the battery's state of charge SoC_{bat}, is evaluated by (3) [17], [18], where SoC_{bat} is the battery state of charge (%), Q_{bat} is the maximum battery capacity (Ah).

$$SOC_{bat} = 100 \cdot \left(1 + \frac{1}{Q_{bat}} \cdot \int_0^t i_{bat}(t)\,dt\right) \tag{3}$$

The battery's charge-discharge cycle is mainly determined by the amount of power available and the power level required by the system. This cycle depends on both available energy capacity and demand dynamics. The battery's State of Charge (SoC) limits is used to define operational constraints, framing minimum and maximum operating thresholds. These limits are used to set safety limits and optimize battery use according to the actual power capacities that can be supplied or absorbed at any given time, as described in (4), where SoC_{batmin} and SoC_{batmin} are respectively the state of charge minimum and maximum.

$$SOC_{bat\,\min} \le SOC_{bat} \le SOC_{bat\,\max} \tag{4}$$

TABLE II. CHARACTERISTICS OF BATTERY AND BIDIRECTIONAL CONVERTER

Electrical Parameters	Values
Battery source	
Q	*648 Ah*
E_0	*273.2 V*
K	*0.0029*
R_b	*0.0038*
A_b	*21.16*
B	*0.094*
SOCbat	*50%*
DC-DC bidirectional converter	
C_{bus}: Capacitor	*3300 µF*
L_{bat}: Inductance	*1 mH*
f: Switching frequency	*10 kHz*

III. ENERGY MANAGEMENT STRATEGIES

This section provides an in-depth explanation of the MPPT control principle and the energy management strategy proposed in this paper.

A. *Principle of MPPT Control for PV*

The photovoltaic (PV) panel, as a generator of electrical energy, converts solar irradiance into electricity through a direct conversion process. Nevertheless, this conversion is subject to the intrinsic variability of solar resources, which induces intermittent and non-linear behavior in energy production. This characteristic adversely affects the stability and performance of the PV system. To mitigate these effects and optimize energy capture, the integration of a dedicated control system is essential. To do this operation , the MPPT algorithms play a crucial role, adapting the operating point of the PV grid in real time to extract the maximum available power. Several MPPT strategies have been proposed in the literature [2], [19], [20], aiming to autonomously control the voltage of each PV module, in order to maximize energy efficiency under varying sunlight and temperature conditions. In the present work, we have opted for the control strategy shown in Figure 2 with the integrated Incremental Conductance (InC) algorithm, whose principle is illustrated in Figure 3, as the method for tracking the maximum power point. The InC algorithm is based on an analysis of the power gradient as a function of voltage (dP/dV), enabling precise estimation of the optimum operating point. In combination with the irradiance sensor, it provides the reference current that is calculated using (5).

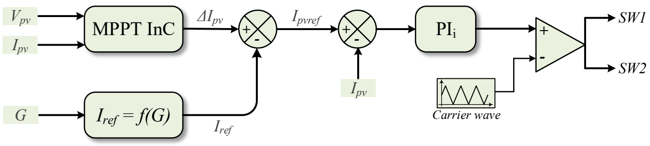

Figure 2. Strategy MPPT Control.

$$I_{ref} = \left(I_{sc} + k_{sc} \cdot (T - 298.15)\right) \cdot \left(\frac{G}{1000}\right) \tag{5}$$

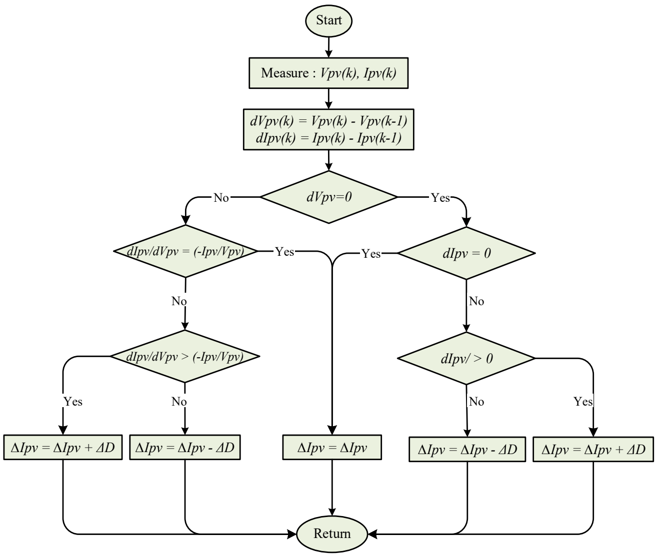

Figure 3. MPPT InC.

B. *Energy Management Strategy Control (EMSC)*

The main objective of this study is to propose an innovative energy management strategy in a micro-grid, based on the use of a Proportional-Integral (PI) regulator, allowing for optimal energy transfer between the different components of the system. A fundamental aspect of this approach lies in maintaining the stability of the direct current DC-bus voltage, which must remain at a predefined reference level, regardless of external disturbances or inherent system uncertainties. The stability of this voltage is indeed crucial to ensure the performance, reliability, and operational safety of the micro-grid.

The proposed method is based on minimizing the error between the measured DC bus voltage (V_{bus}) and the setpoint (V_{busref}) using a robust and systematic control scheme. The micro-grid's electrical system must constantly adapt to variations in the output of PV sources. In this context, battery loading becomes essential to avoid system instability in the event of production deficits and overproduction, thus ensuring balance between supply and demand.

Given that battery is coupled to the DC-bus via a bidirectional DC-DC converter, the PI controller's main task is to drive this converter in buck or boost mode, depending on energy requirements. The reference current, generated by the PI voltage controller, is used to determine the duty cycle applied to the pulse-width modulation (PWM) module, thus effectively regulating converter operation. As shown in Figure

1, PV energy is mainly directed to the loads on the micro-grid and, in the event of excess, to the battery. This strategy ensures precise current and voltage regulation, while maintaining an overall energy balance. It maximizes the use of solar energy while ensuring optimum battery performance during charging and discharging.

The structure of the control circuit is shown in Figure 4, and is based on a PI control loop which generates the appropriate duty cycle to track V_{ref} (fixed at 1000 V). This mechanism allows control of battery charging and discharging operations by leaving the battery current free, unlike a cascade loop controller where this degree of freedom is restricted. The coefficients k_p and k_i of the proportional-integral controllers for PV current and DC bus voltage were determined by (6) to optimize the dynamic response of the system. Table 3 shows the optimal values found for these parameters. The performances obtained were validated by simulation.

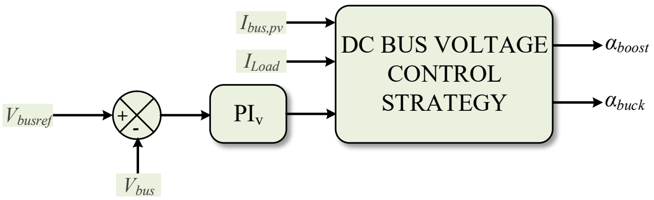

Figure 4. DC-bus voltage control.

$$\begin{cases} k_{pi} = L \cdot \omega_n^2 \\ k_{ii} = L \cdot \omega_n^2 \cdot 2 \cdot \varepsilon \\ k_{pv} = C \cdot \omega_n^2 \\ k_{iv} = C \cdot \omega_n^2 \cdot 2 \cdot \varepsilon \end{cases} , \quad \begin{cases} \omega_n = 2 \cdot \pi \cdot \dfrac{f}{10} \\ \varepsilon = \dfrac{\sqrt{2}}{2} \\ \tau_{(i,v)} = \dfrac{k_{p(i,v)}}{k_{i(i,v)}} \end{cases} \qquad (6)$$

The system's ω bandwidth is restricted to 10% of the control frequency [5], [7].

TABLE III. PI CONTROLLER PARAMETERS

Coefficients	Values
k_{pi}	0.1
k_{ii}	100
k_{pv}	0.1
k_{iv}	1

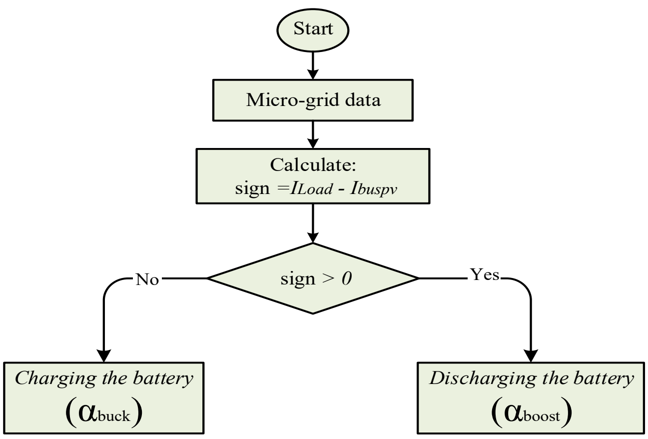

Figure 5. Voltage control strategy.

Figure 5 illustrates the flowchart of the control strategy developed. The battery storage system plays a dual role, both supplying energy and absorbing excess energy. In stand-alone mode, when production exceeds demand, the algorithm commands the battery to charge at a rate compatible with its safety limits, in particular its maximum permissible current. Conversely, in the event of a shortfall in photovoltaic production, the battery supplies the energy required to meet load demand, until it is completely discharged. The energy management system continuously monitors the battery's storage status to ensure safe and efficient operation of the micro-grid.

IV. Simulation Results and Discussion

Following the design of the photovoltaic system, storage device and control strategy, Matlab/Simulink software was used to model and simulate the hybrid power system, with a view to validating the effectiveness of the proposed energy management strategy.

A controlled DC voltage source has been adopted to represent the main DC bus, enabling analysis of system behavior in the presence of line or load disturbances. The simulated weather conditions, illustrated in Figure 6, include the evolution of solar radiation (in W/m²), ambient temperature (in °C) during and the load demanded over a period of 1000 hours. These parameters have a direct influence on the energy output of the photovoltaic modules. The simulated climate profile incorporates realistic scenarios, ranging from optimal sunshine to cloudy episodes and sunset, to assess the robustness of the control strategy in the face of environmental variations, an essential criterion in micro-grid applications.

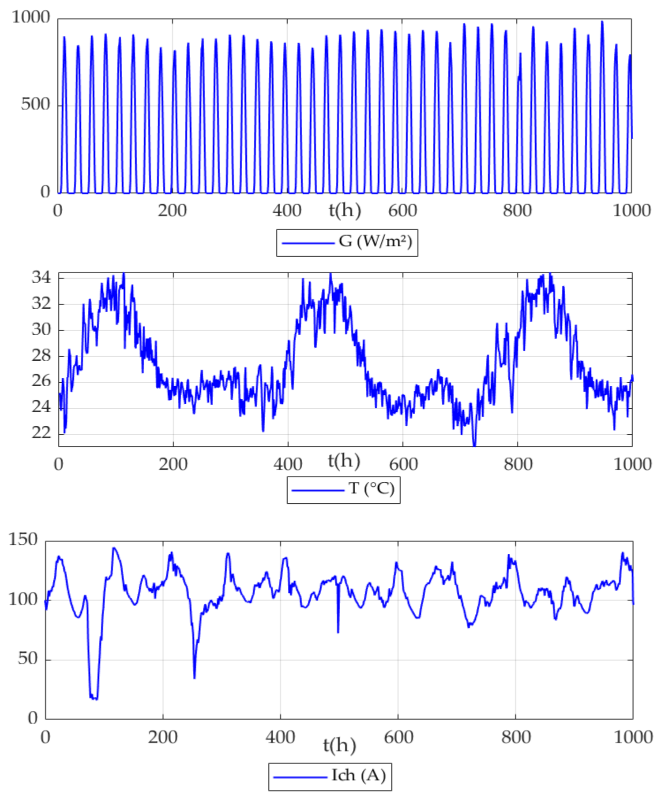

Figure 6. Variations in experimental weather conditions, solar radiation, temperature and load.

The curves in Figure 7 illustrate the temporal evolution of the voltage (V_{pv}) and current (I_{pv}) supplied by the photovoltaic modules. It can be seen that the system efficiently follows variations in irradiation and temperature, ensuring optimum production. This demonstrates the ability of the MPPT algorithm and its control strategy to dynamically adapt the operating point of the PV generator.

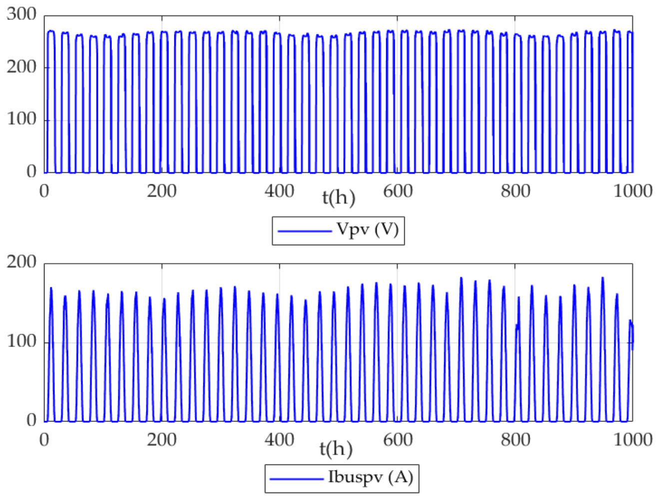

Figure 7. Waveform of the current and voltage on the PV side.

The result of the waveforms shown in the Figure 8 compares the current measured at the output of the photovoltaic array with the reference current generated by the MPPT controller. The precise alignment between the two curves demonstrates the performance of the incremental conductance algorithm, which rapidly adjusts the reference current in response to changes in sunlight, ensuring high energy efficiency.

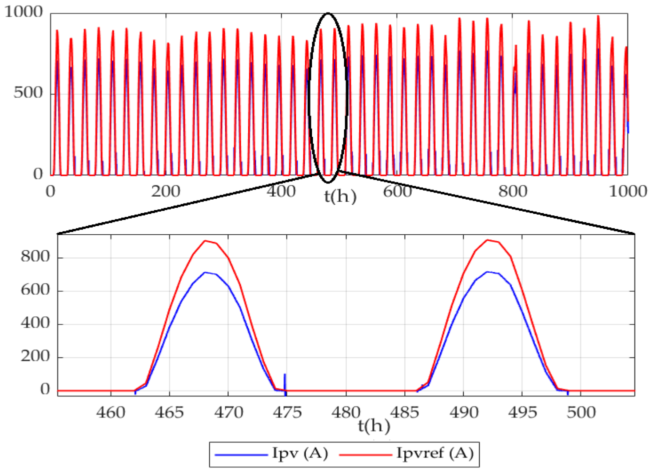

Figure 8. Waveform of the current and its reference on the PV side.

The DC bus voltage is regulated around a setpoint of 1000 V. The evolution of its result over the course of the experiment is illustrated in Figure 9. Thanks to the PI controller and the control strategy, effective regulation is achieved even in the presence of disturbances on the load or generation side. The stability of this voltage is essential to ensure the smooth operation of all equipment interacting in the system, particularly the micro-grid receivers.

The waveform results shown in Figure 10 demonstrate the battery's response to system requirements. Current variations indicate the charging and discharging phases in relation to solar energy availability and load demand. Voltage remains within nominal ranges, reflecting the correct sizing of the bi-directional converter and the reliability of the management system.

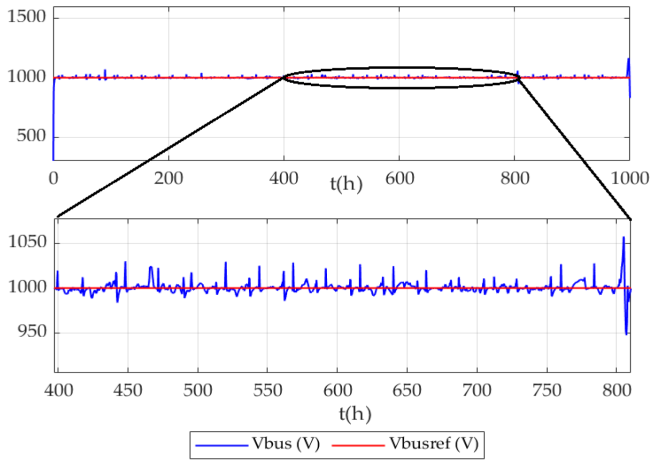

Figure 9. DC-bus voltage.

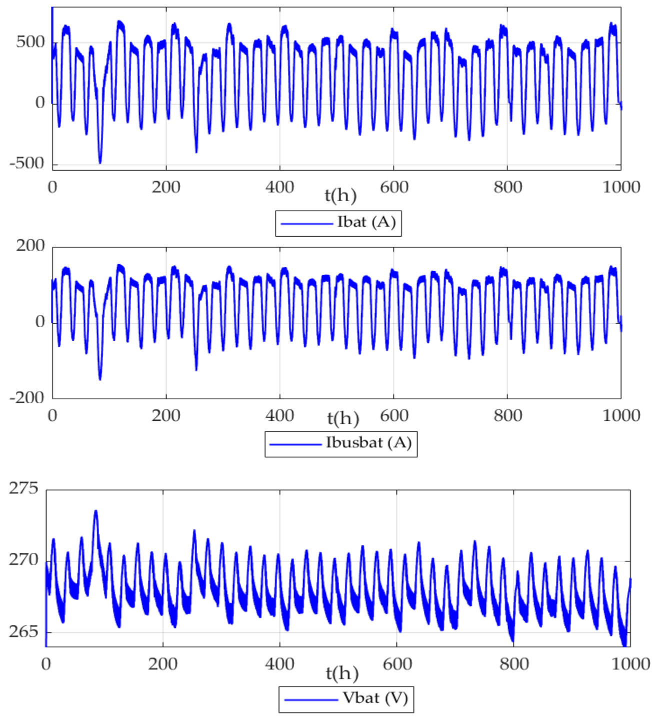

Figure 10. Waveform of the voltage and current on the battery side.

Figure 10 shows the state of charge of the battery pack. It can be seen that during the period of overproduction, the battery's state of charge increases due to the excess solar energy production, conversely, when we are in deficit of production, the battery contributes by discharging to ensure the balance between supply and demand. This confirms that the proposed DC bus voltage control strategy responds effectively to system constraints, with better performance in terms of stability.

The results in Figure 9 and Figure 10 confirm that the proposed DC bus voltage control strategy effectively meets the system's constraints, with better performance in terms of stability.

The resulting waveforms in Figure 11 illustrate the power flows involved in the system. We can see how the energy produced by the PV is shared between the load (micro-grid) and the battery. When PV energy is insufficient, the battery takes over. The EMSC thus ensures efficient dynamic management, avoiding losses and maintaining energy balance.

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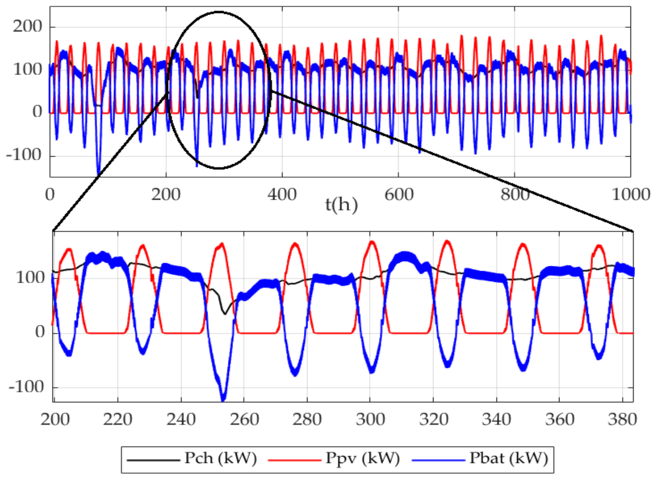

Figure 11. Waveform of the power.

V. CONCLUSION AND FUTURE WORK

In this paper, a control and energy management strategy for a stand-alone PV–battery hybrid micro-grid has been proposed, specifically designed for rural electrification in Guinea. By combining an Incremental Conductance MPPT algorithm with Proportional–Integral controllers, the system ensures both maximum photovoltaic energy extraction and robust DC-bus voltage regulation. The proposed approach enables efficient coordination between PV generation and battery storage, thereby improving energy utilization, enhancing system stability, and reducing current stress on the load. Simulation results in Matlab/Simulink under realistic irradiance and load conditions confirm the effectiveness of the proposed strategy, demonstrating stable DC-bus operation at 1000 V, optimized battery charge/discharge management, and improved overall efficiency of the micro-grid. These findings indicate that the proposed control system is well suited for off-grid rural applications where reliability and energy autonomy are critical. Future work will focus on experimental validation using a physical micro-grid test bench, as well as the integration of additional renewable sources and advanced predictive energy management techniques to further enhance system resilience and scalability.

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