Sustainable energy empowerment in remote regions wind-solar system with intelligent management

Rabah Rouas[1], Madjid Sibrahim[1], Said Aissou[2], Salah Haddad[1]
[1]Laboratory of Advanced Technologies in Electrical Engineering, Faculty of Electrical Engineering and Computer Science, Mouloud Mammeri University, Tizi-Ouzou, Algeria
[2]Laboratory of Renewable Energy Mastery (LMER), Faculty of Technology, University of Bejaia, Bejaia, Algeria

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ABSTRACT

This paper presents a device designed to provide continuous electrical energy to isolated areas where connection to the power grid is expensive and unprofitable. This objective is achieved through a system that combines a wind turbine and photovoltaic panels as primary energy sources, with storage batteries and a diesel generator serving as backup sources. The main contribution of this work is characterized by the ability to ensure uninterrupted electrical power supply, even on days when renewable energy sources are less favorable. This intermittency is due to the random nature of these sources, as well as their dependency on weather and climatic conditions. Therefore, we sized each component of the hybrid system to meet the maximum required load individually under the most favorable conditions. We then modeled each energy conversion chain and developed power control laws to ensure effective set point tracking. Finally, we implemented a hierarchical energy management algorithm to define the operating modes of the hybrid system's sources, aiming to produce as much power as the load requires while prioritizing the use of renewable energy sources to minimize reliance on the storage system and the diesel generator.

Corresponding Author:

Rabah Rouas
Laboratory of Advanced Technologies in Electrical Engineering
Faculty of Electrical Engineering and Computer Science, Mouloud Mammeri University
B.P.17 RP, 15000 Tizi-Ouzou, Algeria
Email: rabah.rouas@ummto.dz

1. INTRODUCTION

Researchers worldwide encourage producers and users to shift to renewable energy resources, particularly solar and wind energy. Moreover, to meet current market requirements, energy forms would replace fossil resources in this context [1]-[6], as their use is inexhaustible, non-polluting, and well-suited to future market requirements. The global demand on energy could be sufficiently satisfied through renewable energies, as this form of energy has a significant potential [7]. The increasing adoption of renewable energy sources like solar, wind power is crucial for addressing climate change and reducing the dependence on fossil fuels. As technology advances and economies of scale improve, renewables become more competitive, making them an increasingly attractive option for electricity generation. Achieving nearly 50% of global electricity generation from renewables by 2026 would mark a significant milestone in the transition to a more sustainable energy future [8]. Nevertheless, technologies applied to renewable energies often rely on one source of energy. For this reason, energy use based on solar energy (PV) or wind power is insufficient to satisfy the users' needs especially that these forms of energy production highly depend entirely on the weather, climate change, and natural hazards [9]. Consequently, the monitoring and management of this instability is imperative, by integrating a complementary energy storage system [2].

Indeed, several multi-sources energy system designs have been proposed with different power control features. Some of them are based on logical states and others on intelligent algorithms. The latter are more interesting, especially for autonomous applications. A great deal of publications has been devoted to the study of power management in multi-sources [2], [3], [10]-[13]. Typically, the management is still based on power balance. Thus, some authors have suggested various methods for power management and monitoring. Consistently, in articles [14]-[16] the monitoring system uses fuzzy logic. Different authors suggest various strategies, with [17] using levelness and [18] relying on power balance. Additionally, power management seems to be controlled by microcontrollers, as evidenced in with [16]-[21].

This study describes wind-photovoltaic system's power management and control. For this purpose, we will first present the global system under consideration. Then, we will suggest an energy management strategy that will deliver power references for each source (wind, photovoltaic, battery, and diesel generator) for an optimal, uninterrupted load supply. The load is represented by a variable resistor. Finally, to validate this management strategy, we consider some simulation scenarios that the system will likely undergo.

2. GLOBAL SYSTEM PRESENTATION

This study presents a hybrid system that combines two renewable energy sources: a photovoltaic generator to convert solar energy and a wind generator to convert wind energy. The primary purpose is to use the hybrid wind-photovoltaic system to supply electrical energy to remote areas where the grid connection is prohibitively expensive. Moreover, the system is equipped with storage batteries and a diesel generator that would provide backup power in case of a lack of sunlight or wind. These energy sources are connected to the same direct current DC bus via converters, whose role is to ensure power control and a constant DC voltage despite load variations. This overall system is illustrated in Figure 1.

The wind turbine conversion chain comprises a 3 kW induction generator, self-excited by a three-phase bank of capacitors, allowing the conversion of the wind energy into electrical energy [22]-[25]. This generator can provide one-third of its maximum power under optimal conditions. A pulse-width modulation (PWM) rectifier equipped with a neural network-based direct power control (DPC) control law enables the asynchronous generator to follow a given active power reference while maintaining a fixed rectifier output voltage, as shown in Figure 2 [26].

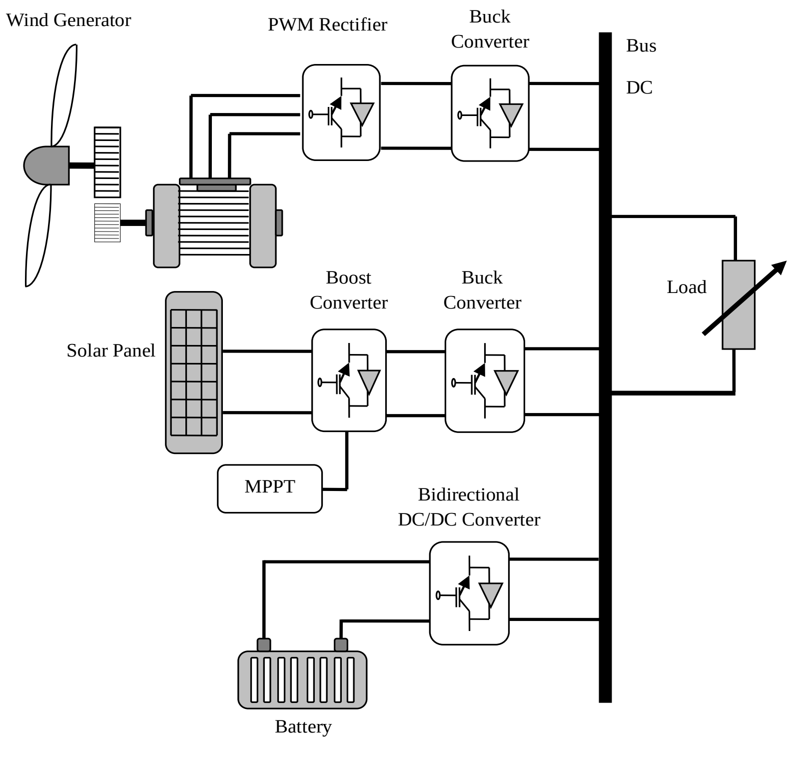

Figure 1. Proposed studied DC microgrid

A regulated DC/DC series converter (chopper) allows having a specific voltage useful to the connection to the DC bus. The photovoltaic conversion chain is composed of a combination of ten solar panels, each with a power of 60 W, converts solar energy into electrical energy. The panels are connected to a DC/DC converter (step-up chopper) equipped with a maximum power point tracking (MPPT) (perturb and observe with reference tracking) control to ensure optimal operating conditions for all the panels, as shown in Figure 3 [3], [27], [28]. A regulated DC/DC series chopper that enables the desired voltage required by the connection to the DC bus. The storage chain comprises a lithium-ion battery initially charged and a bidirectional DC/DC converter, suitable for an energy storage system that charges and discharges the battery shows in Figure 4 [27].

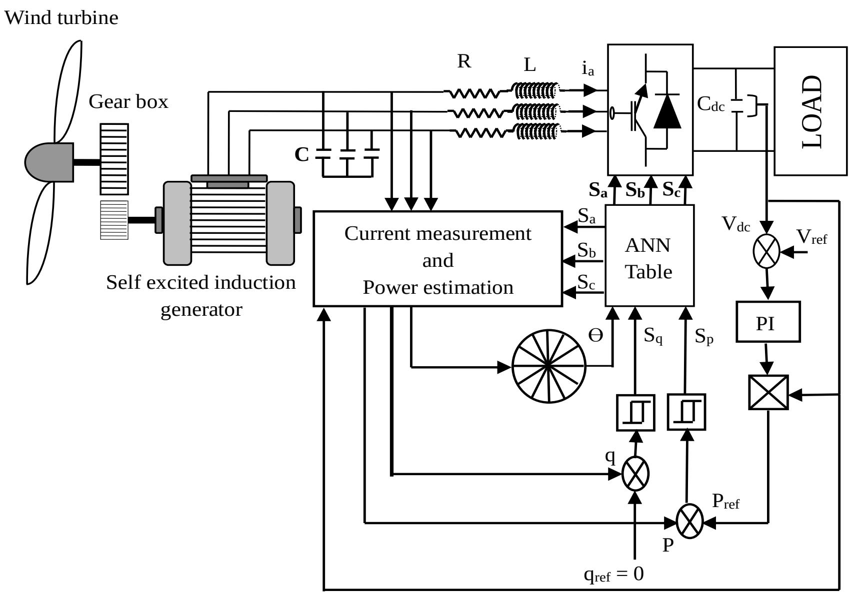

Figure 2. Direct power control diagram for wind energy

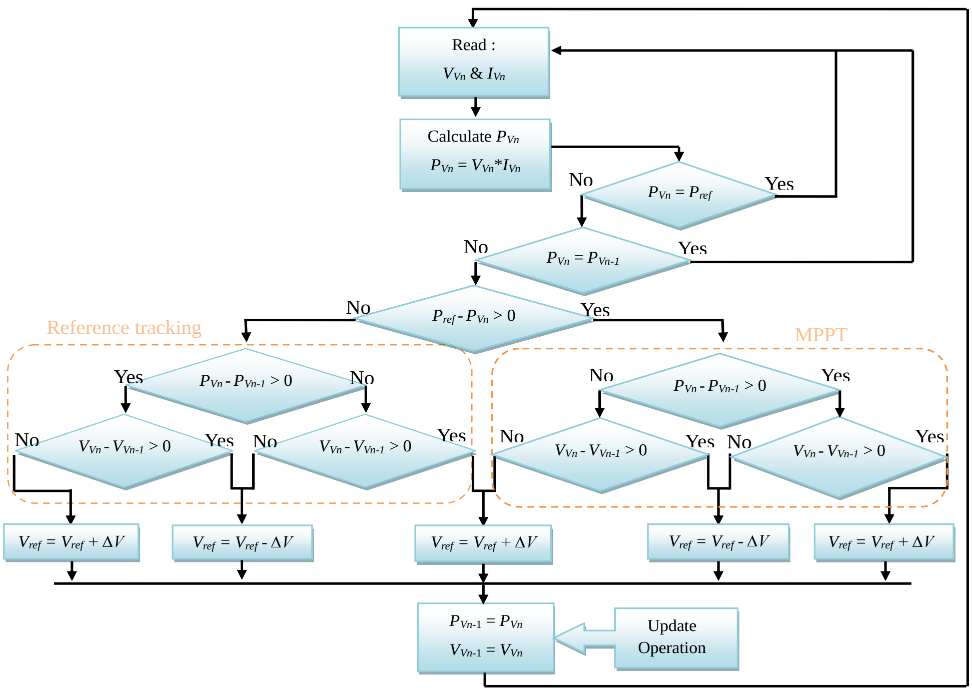

Figure 3. Perturb and observe MPPT with reference tracking

2.1. Model of PV array

In the technical literature we find several models of photovoltaic generators (with one, two or three diodes). They differ in the number of parameters involved in the calculation of the final value of the voltage and current of the photovoltaic generator. The single-diode model is the most commonly cited in the literature. The equivalent circuit shown in Figure 5 characterizes it. It consists of a current source symbolizing the conversion of luminous flux into electrical energy, a shunt resistor R_{sh} characterizing the leakage current at the cell surface due to the non-ideality of the PN junction, and impurities near the junction. A series resistor Rs represents the various contact and connection resistances [27].

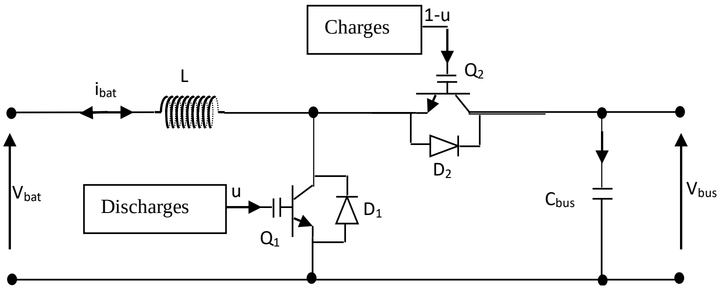

Figure 4. Electrical diagram of the chopper converter

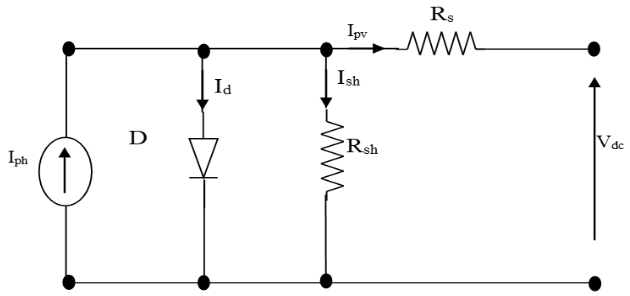

Figure 5. Equivalent circuit of solar cell

Figure 5, the (1) gives the current I_{pv} of the photovoltaic cell under standard operating conditions.

$$I_{pv} = I_{ph} - I_d - I_{sh} \tag{1}$$

Where I_{ph} : the photo-current, I_d: polarization of the PN junction current, I_{sh}: current in the resistor R_{sh}. The current expression of the solar cell is given by (2):

$$I_{pv} = I_{ph} - I_0 \left(e^{q\left(\frac{V+R_{sh}}{n.k.T}\right)} - 1 \right) - \frac{V_{pv}+I.R_s}{R_{sh}} \tag{2}$$

Where: V_{pv}: cell voltage [V], I_0: saturation current [A], Rs: cell series resistance [Ω], R_{sh}: cell shunt resistance [Ω], T: cell temperature [°K], q: the electron's charge, e = 1.6 *10-19 [C], K: Boltzmann constant (1.3854*10-2 [JK -1]), and n: the diode quality factor.

2.2. Dynamic model of the generator

The asynchronous generator model in Park's reference frame is written as in (3):

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & -\omega_s.L_s & 0 & -\omega_s.L_m \\ \omega_s.L_s & R_s & \omega_s.L_m & 0 \\ 0 & \omega_r.L_m & R_r & -\omega_r.L_r \\ \omega_r.L_m & 0 & \omega_r.L_r & L_r \end{bmatrix} . \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} + \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} \frac{di_{ds}}{dt} \\ \frac{di_{qs}}{dt} \\ \frac{di_{dr}}{dt} \\ \frac{di_{qr}}{dt} \end{bmatrix} \tag{3}$$

where Rs, Rr, Ls, and Lr are the stator and rotor resistances per phase and the cyclic self-inductances, respectively, and Lm is the magnetizing inductance. It's important to note that in the model of the induction machine operating as a generator, the saturation must be taken into account, since it determines the operating point) [22]-[25]. Taking saturation into account means considering the magnetizing inductance Lm as variable as a function of the magnetizing current im. The MATLAB-Simulink program for the self-excited induction generator is based on the system of (3) [22]-[25]. The under-load self-excitation process is modelled as in (4) [22]-[25].

$$p.\begin{pmatrix} v_{ds} \\ v_{qs} \end{pmatrix} = \begin{pmatrix} \frac{-1}{R_L.C} & 0 \\ 0 & \frac{-1}{R_L.C} \end{pmatrix} \begin{pmatrix} v_{ds} \\ v_{qs} \end{pmatrix} - \frac{1}{C} \begin{pmatrix} i_{ds} \\ i_{qs} \end{pmatrix} \quad (4)$$

Where R_L is the load resistance and C is the self-excitation capacity. The induction machine parameters and the photovoltaic panel electrical parameters are shown in Tables 1 and 2, respectively.

Table 1. Induction machine parameters

Parameters	Value	Unit
Rated power (Pa)	3	kW
Rated speed (Ωn)	1415	rpm
Number of pole pairs (p)	2	-
Stator resistance (Rs)	1.615	Ω
Rotor resistance referred to the stator (Rr)	3.926	Ω
Stator leakage induction (lss)	0.0126	H
Rotor leakage induction referred to the stator (lrs)	0.0126	H

Table 2. Photovoltaic panel electrical parameters

Parameters	Value	Unit
Peak power (P_{max})	60	W
Voltage (V_{mp})	17.2	V
Current (I_{mp})	03.4	A
Open circuit voltage (V_{c0})	21.1	V
Short circuit current (I_{sc})	03.8	A
Nomber of cells	36.0	-

3. MANAGEMENT STRATEGIES OF THE HYBRID SYSTEM

The management strategy proposed in this paper aims to generate power references for each source, to ensure an optimal supply with no load interruption. Therefore, the study outlines an algorithm for power flows management between the various sources. The latter follows an "all or nothing" logic rule, targeting activating or deactivating the sources as the hybrid system state evolves. The role of this algorithm, which is located at the core of the hybrid system, is displayed in Figure 6.

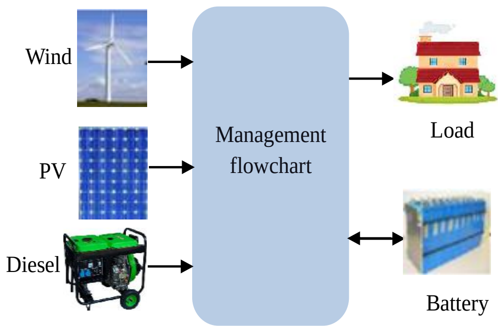

Figure 6. Block diagram of the management strategy

The objective of the management algorithm is to define the operating points of the hybrid system's sources, thus producing as much power as required by the load. This operation is established by prioritizing the renewable energy sources and sparing the storage system and the diesel generator as much as possible. Furthermore, the management algorithm must optimize the storage battery to extend its lifespan, as a reasonable estimation of its state of charge or discharge (SoC) is necessary. Therefore, it is advisable to reduce the battery's load and use energy from renewable sources to preserve the battery. However, in critical situations involving insufficient renewable energy sources and low battery SoC, the diesel generator must support the hybrid system and supply the load.

The management strategy developed in this study is based on conditional statement rules. This strategy considers the wind conversion system as the leading source to power the load. Therefore, the photovoltaic conversion system is activated only when the former does not meet the load demand. Furthermore, the battery is used in case of power production lack. It is also a storage system in the case of overproduction. Finally, the diesel generator is considered a last resort. Energy production sources operate in maximum power point mode, and the hybrid system is isolated. Consequently, we have provided a dissipative load that serves as an "overflow" for possible overproduction. The operating scheme of this algorithm is shown in Figure 7, where: P_W is the wind power, P_{PV} is the photovoltaic power, P_{ch} is the power required by the load, SoC is the charged and discharged state of the battery (state of charge), ΔP_1 is the difference between the wind power and the power requested by the load, given by the following equation: $\Delta P_1 = P_w - P_{ch}$, ΔP2 is the difference between the sum of the two powers, namely the wind and photovoltaic, and the power requested by the load, given by the following equation: $\Delta P_2 = (P_{pv} + P_w) - P_{ch}$.

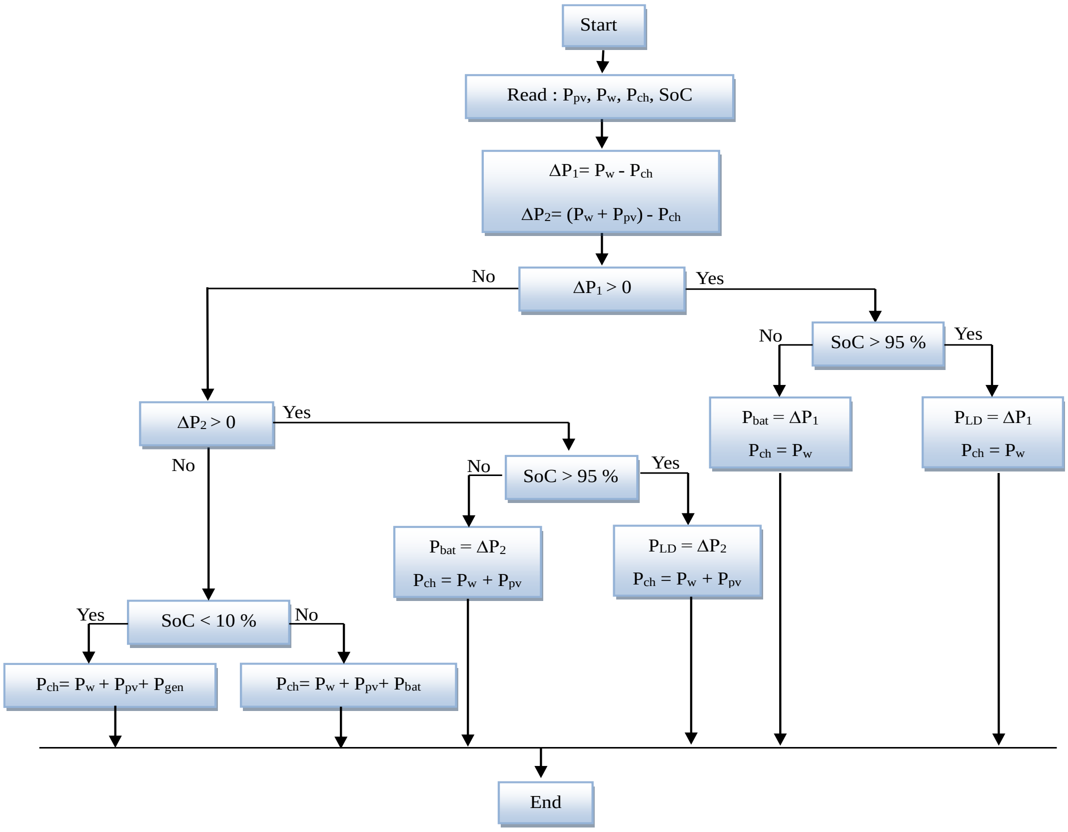

Figure 7. Energy management flowchart

4. RESULTS AND DISCUSSION

To validate the developed management strategy by simulation tests, several possible simulation scenarios to be encountered by the hybrid system were considered. The simulation results are given in the presented figures. The different scenarios are designed to involve all the energy sources of the hybrid system.

4.1. Case where ΔP1 > 0, ΔP2 > 0 and SoC [10-95%]

This case illustrates a simulation of the overall system, where we made a variation of the charging power, going from 600 W to 1400 W at t = 4 s, then decreasing to 1200 W at t = 8 s. In this case, the battery is charged to 50%. This scenario allowed us to see the algorithm's reaction to this situation. The results obtained are shown in Figures 8(a)-8(d).

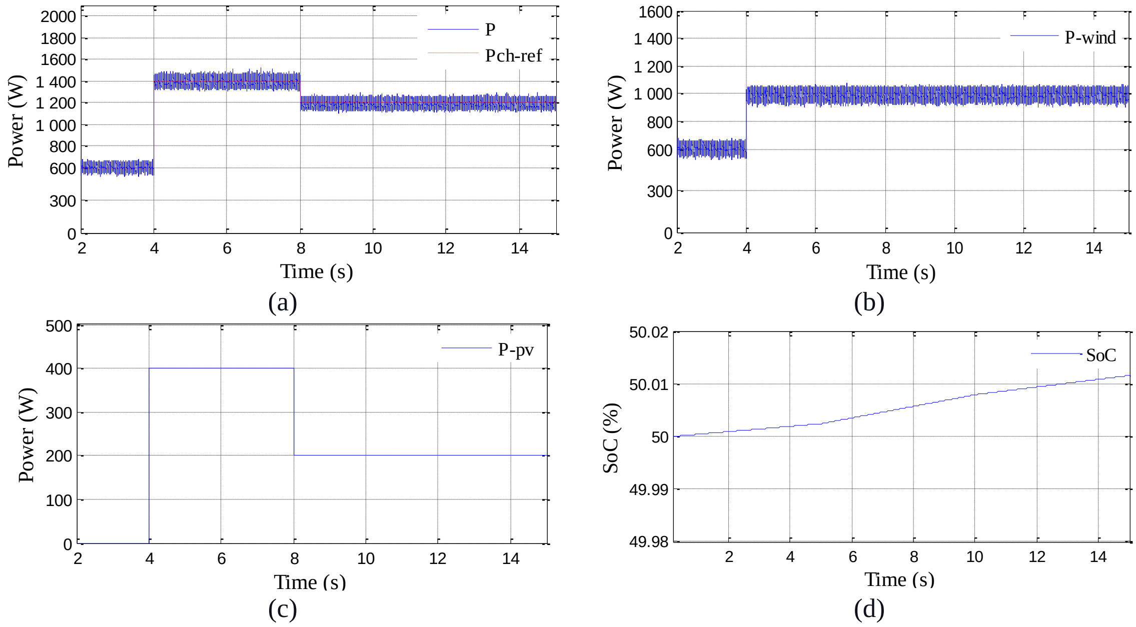

Figure 8. Simulation results for the first scenario: (a) power produced by the global system, (b) power delivered by the wind generator, (c) power supplied by the photovoltaic generator, and (d) battery SoC curve

4.2. Case where ΔP1 > 0, ΔP2 > 0 and SoC > 95%

In this case, we repeated the previous experiment, but the battery was charged to more than 95%. The results obtained are shown in Figures 9(a)-9(c). The simulation results show that when the battery is charged (Figure 9(b)), the auxiliary load dissipates the surplus power, as shown in Figure 9(c).

4.3. Case where ΔP1 < 0, ΔP2 < 0 and SoC < 10%

For the last scenario, we performed a power variation until the two main sources could no longer satisfy the load considering that the battery is at its minimum state of charge. This situation imposes the triggering of the diesel generator, which must supply the load demand. It is worth noting that the generator is seen as a constant source. The results obtained are shown in Figures 10(a)-10(e).

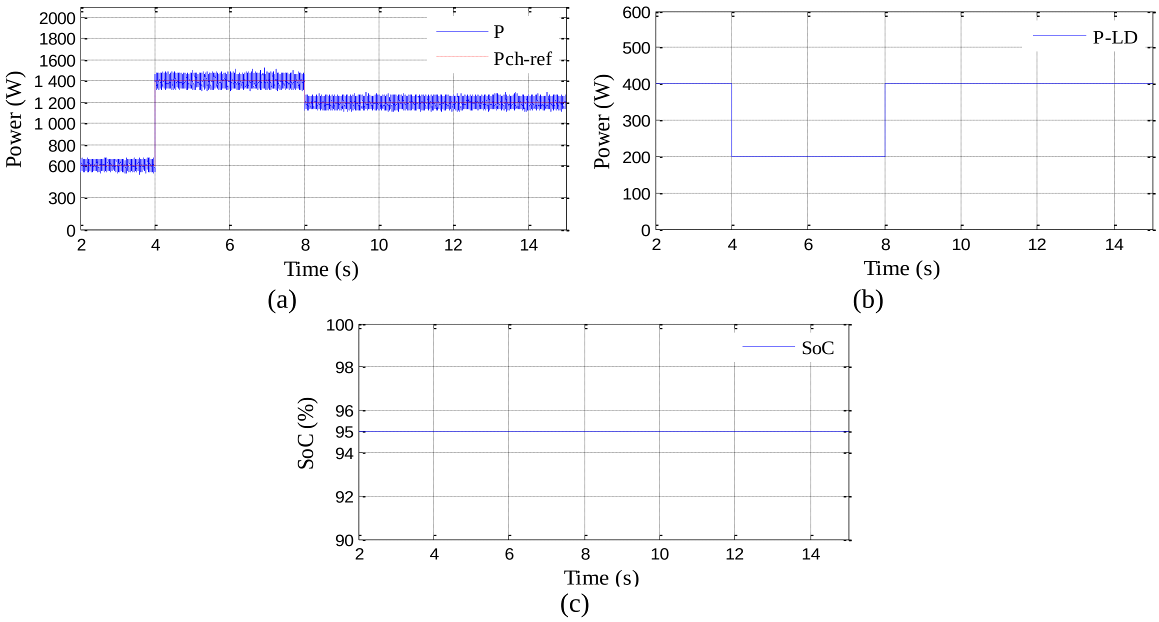

Figure 9. Simulation results for the first scenario: (a) power produced by the global system, (b) the surplus power curve, and (c) the battery SoC curve

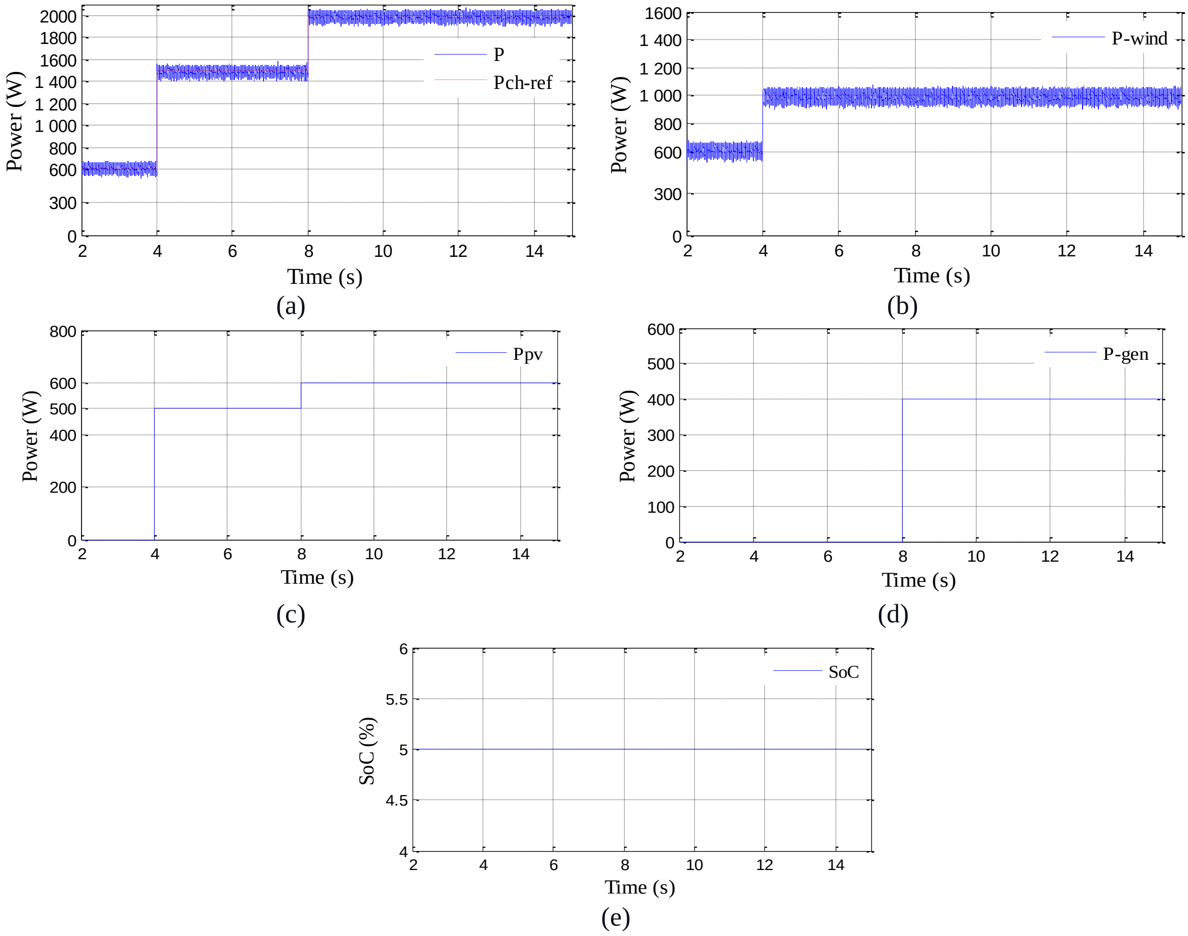

Figure 10. Simulation results for the third scenario: (a) power produced by the global system, (b) power produced by the wind generator, (c) power produced by the photovoltaic generator, (d) power produced by the diesel generator, and (e) SoC of the battery

From 0 to 4 s, the wind generator alone is sufficient to cover the needs of the load (Figure10 (d)). From 4s onwards, the wind generator can only supply a part of the power demanded. Then, the photovoltaic generator comes into play to supply the missing power (Figure 10(b)). At t = 8 s, an additional power demand involves the diesel generator (Figure 10(e)), as the battery is discharged (Figure 10(c)). These three scenarios show that our algorithm has responded accurately to the basic purpose of its design. Indeed, the system was designed to satisfy the load demand considering the following components: The wind conversion system as the leading source, the photovoltaic system as a backup, and the battery as a storage system in case of overproduction or a backup source in case of production shortage. Additionally, the diesel generator is considered as an ultimate backup source.

5. CONCLUSION

This paper described the analysis of a hybrid electric energy system, including a wind turbine generator associated with photovoltaic panels and a storage system. First, we gave a presentation of the overall design. Then, we connected the energy sources to the same DC bus through power electronic converters, ensuring both the power control and a constant DC voltage, despite the load variations. Afterward, we developed an energy management algorithm to identify the hybrid system's operating points and to produce the required energy as requested by the load. This operation prioritizes renewable energy sources and spares the conventional energy sources (a diesel generator, batteries). Finally, to validate the management strategy, we simulated our algorithm's response to a power demand profile. These responses include the scenarios that the system is likely to encounter.

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BIOGRAPHIES OF AUTHORS

Rabah Rouas was born in Tizi-Ouzou on the 23 rd of November 1986. In 2007, he earned his baccalaureate degree in science, and in 2012, he obtained his master's degree in electrical engineering from the Mouloud Mammeri University in Tizi-Ouzou, Algeria. Since 2013, he has been a freelance teacher at the university. In 2018, he was awarded his Ph.D. in electrical engineering by the University of Mouloud Mammeri in Tizi-Ouzou. He is presently serving as a senior lecturer at the same university, and his research pursuits focus on power quality and electrical machine control. He can be contacted at email: rabah.rouas@ummto.dz.

Madjid Sibrahim was born on July 7, 1984, in Tizi-Ouzou, Algeria, pursued his academic journey at Mouloud Mammeri University in Tizi-Ouzou. He obtained his BSc in Exact Sciences in 2005 and continued his education to earn his MSc in Electrical Engineering in 2010 from the same university. he began his career as a freelance lecturer at Mouloud Mammeri University in 2011. In 2015, he achieved a significant milestone in his academic journey by completing his Ph.D. in Electrical Engineering from the same University. He obtained its university habilitation in February 2024. Currently, he is a teacher-researcher at Mouloud Mammeri University, where he continues to impart knowledge and conduct research in his areas of interest. His research interests include power quality, motor control, artificial intelligence and renewable energies, reflecting his commitment to advancing sustainable and efficient energy solutions. He can be contacted at email: madjid.sibrahim@ummto.dz.

Said Aissou was born in Algeria in 1984. He is currently a teacher in the Science and Technology Department and conducts research activities at the Laboratory of Renewable Energy Mastery (LMER). He studied at the University of Bejaia, Algeria, where he received his master's degree in electrical engineering in 2012 and later got his Ph.D. in Electrical Engineering from the same university in 2016. His research interests include renewable energy integration, power system analysis, and electric vehicles. He can be contacted at email: said.aissou@univ-bejaia.dz.

Salah Haddad was born in Tizi-Ouzou, Algeria, on February 23, 1961. He completed his Eng. degree in Electrical Engineering from the Mouloud Mammeri University of Tizi-Ouzou, Algeria, in 1985. In 1991, he earned his Ph.D. in Electrical Engineering from Institut National Polytechnique de Loraine", Nancy, France. Currently, he is a professor at Mouloud Mammeri University of Tizi-Ouzou, where he has been a faculty member since 1992. His research interests include exploring power quality, control of electrical machines, and discovering new approaches to renewable energy. He can be contacted at email: salah.haddad@ummto.dz.