An optimal energy management strategy for a stand-alone PV/wind/battery hybrid energy system

Otmane Zebraoui[1], Mostafa Bouzi[2], Badr Nasiri[3]
[1]SmartiLab Laboratory, Moroccan School of Engineering Sciences (EMSI), Honoris United Universities, Rabat, Morocco
[2]Department of Electrical Engineering, Faculty of Sciences and Technology, Hassan First University, Settat, Morocco
[3]Department of Physics, Faculty of Science, University Moulay Ismail, Meknes, Morocco

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ABSTRACT

This paper presents an optimization study of a stand-alone hybrid energy system that includes a photovoltaic energy generator, a wind energy generator, and lithium-ion storage batteries. In the proposed system architecture, solar, and wind sources are utilized as the primary power generators, while batteries serve as a secondary storage to ensure system autonomy across varying weather conditions. The aim is to improve system performance through an optimal energy management strategy that addresses operational constraints and electrical load needs while managing energy flow between sources and controlling the storage system. To manage energy flow between sources and load, an intelligent approach using a hierarchical algorithm is proposed to configure the optimal operating mode based on the power from both sources, load power, and battery state of charge. Additionally, a controller is developed to manage battery operating modes, ensuring state of charge (SOC) limits and maintaining a constant direct current (DC) bus voltage. Under varying operating conditions, the simulation results show the efficiency of the proposed management strategy in maintaining the power balance between supply and demand, providing a stable and continuous power supply, and keeping the batteries SOC within its limits and the DC bus voltage at its reference value.

Corresponding Author:

Otmane Zebraoui
SmartiLab Laboratory, Moroccan School of Engineering Sciences (EMSI), Honoris United Universities
Rabat, Morocco
Email: otmanezebraoui@gmail.com

1. INTRODUCTION

Nowadays, the electrification of rural areas is one of the main global concerns, particularly in developing countries, as there are isolated sites that do not have access to the electrical grid and still lack electricity. As well, the main grid extension is not always practical, cost-effective or affordable for rural residents. Therefore, the development of off-grid decentralized electricity generation systems offers an alternative for autonomous electrification in isolated areas. These systems typically combine renewable sources, fossil fuels, and storage batteries to ensure independent electrification away from the main grid [1]-[3]. One of the proposed solutions is multi-source systems based on renewable solar and wind energy, which are currently the most preferred and represent the future of electricity production due to their abundance and sustainability, providing clean alternatives to face climate change and growing pollution problems [4], [5]. Nevertheless, these hybrid systems have some disadvantages that influence their reliable use to produce stable and continuous power under all operating conditions. Among these disadvantages are mainly the non-linear characteristics of photovoltaic and wind generators and the difficulty of operating these systems at their optimum power points due to fluctuating solar and wind energy resources.

Due to the intermittency of renewable sources and the mismatch between energy generation and load demands in isolated sites, optimizing system efficiency is necessary to overcome operational challenges caused by highly uncertain weather conditions. Using control techniques to maximize the power generated by the sources, and system energy management strategies to better meet the load needs. Recently, these multi-source systems caught the attention of researchers with studies of sizing [6], [7], energy management [8]-[10], optimization and control [11]-[13]. In this context, the present research work contributes to promoting the use of hybrid energy systems in isolated sites. Therefore, our main objective is to model and optimize a hybrid system consisting of photovoltaic and wind energy conversion chains along with an energy storage system. To enhance the efficiency of the studied photovoltaic (PV)/wind/battery system, we propose an energy flow management strategy using a multidirectional direct current (DC) bus to control the electrical load supply based on the power generated by the sources and the energy stored in the batteries. Also, we are developing a battery system controller to optimize its usage and manage charge/discharge modes, including DC bus voltage regulation via a bidirectional power converter.

In the literature, there are many studies devoted to the energy management of a hybrid system using different methods. Some of them are based on conventional algorithms and others on intelligent approaches such as fuzzy logic (FL), artificial neural network (ANN), and genetic algorithm (GA). In general, these management approaches are based on the system power balance equation. Sabiri *et al.* [14] proposed an energy management architecture for a multi-source system composed of a wind turbine (DFIG), photovoltaic panels (PV), and batteries. The developed architecture uses a synthesis algorithm for the states of the sources and batteries to manage energy distribution in harmony with the load and the batteries via a multidirectional DC bus. Lagouir *et al.* [15] presented a comparative study of two management strategies based on the Petri net (PN) and fuzzy logic (FL) to control an AC/DC hybrid microgrid. The management system developed takes into account power balancing, the limited production of renewable sources, load shedding and the grid supply limitation. Zerk *et al.* [16] proposed a robust control strategy for the management of a PV/wind/battery hybrid system. The strategy developed is based on controlling the DC bus and managing the system energy using fuzzy logic. Das and Akella [17] have developed a control strategy to manage the power flow of a PV/wind/battery hybrid system to balance energy generation and load power. The proposed strategy uses a fuzzy logic controller to charge or discharge the batteries in order to suppress the power fluctuation, provide quality power to the load and maintain the batteries state of charge (SOC) within authorized limits. Roumila *et al.* [18] presented intelligent supervision of a wind/photovoltaic/diesel hybrid system with storage batteries. The proposed supervisor is based on the fuzzy logic intelligent technique, allows to determine the different system operating processes according to the weather conditions and also to control the state of charge of the storage system in order to avoid breakdowns and extend the battery life. Serir *et al.* [19] proposed a supervision and energy management algorithm of a multi-source pumping system with storage batteries. The developed algorithm allows to manage the system operating modes and to meet the electrical load requirements through efficient use of the batteries. In our case, the proposed energy management strategy is based on a hierarchical approach developed by fuzzy logic. This management approach allows us to configure several system operating modes to better meet the electrical load demands, taking into account the power supplied by the sources, the load power, and the batteries state of charge.

This paper is structured as follows: in the next section, we present a studied system description and modeling. Then, in section 3, we present the proposed energy management strategy to optimize system operation. The system simulation by applying the developed management approach is also presented in section 4, to show the proper system operation under variable weather conditions. In section 5, we discuss the obtained simulation results. Finally, in section 6, a general conclusion summarizing the main results of this work is given, as well as some perspectives envisaged in our future works will be presented.

2. HYBRID ENERGY SYSTEM: DESCRIPTION AND MODELING

In the literature, different architectures of hybrid energy systems have been developed to ensure the energy needs demanded by stand-alone applications in isolated and remote sites [9], [17]. The proposed hybrid architecture is presented in Figure 1. It consists of two photovoltaic and wind energy conversion subsystems, which are considered primary sources of energy to supply a DC load through a multidirectional DC bus. Since these two energy sources depend on weather conditions, in particular, solar irradiation, and wind speed, a storage system is used as an auxiliary source to supply the electrical load when there is a lack of power produced by both photovoltaic and wind generators. Therefore, guarantee autonomy and security of energy supply whatever the weather conditions. All three sources are connected to the DC bus via appropriate static converters, a DC/DC boost converter for the generators and a buck/boost converter for the storage batteries. In addition, with the objective of better exploiting the proposed hybrid system, controllers are developed to improve the performance of the PV and wind subsystems, as well as to manage the system's energy flow and control the storage system. In the following, a detailed modeling of the system is presented.

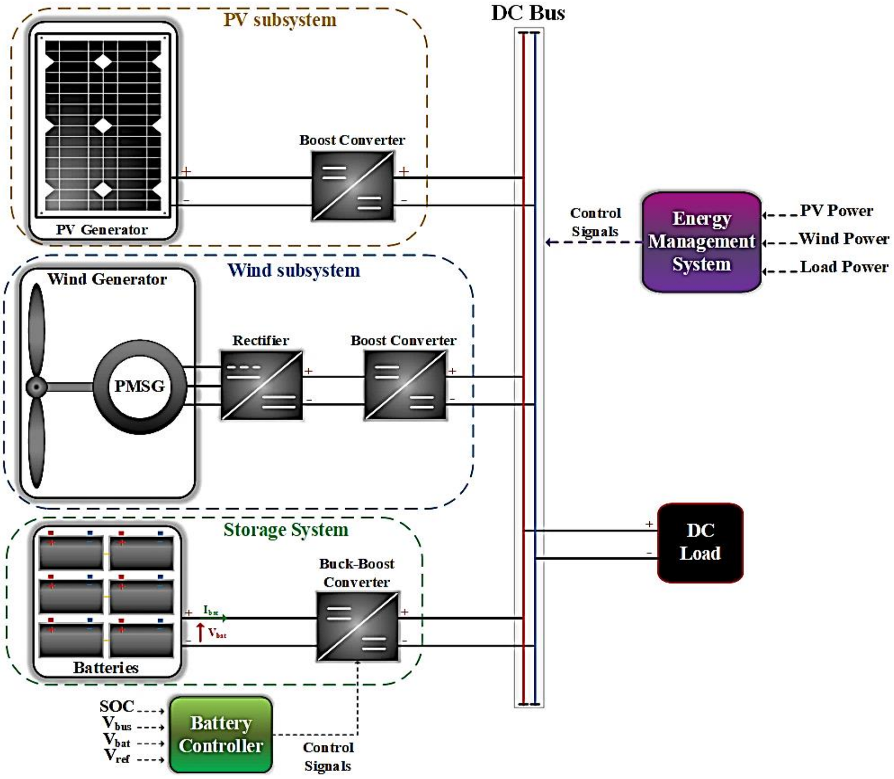

Figure 1. Hybrid energy system architecture

2.1. Modeling of PV system

The photovoltaic subsystem contains photovoltaic panels and a DC/DC boost converter as an adaptation interface between the PV generator and the electrical load. Generally, a photovoltaic generator is made up of several photovoltaic cells connected in series and/or in parallel to obtain the required power at the output. A photovoltaic cell is composed of a p-n semiconductor junction which, thanks to the photovoltaic effect, converts solar irradiation directly into electricity. Figure 2 illustrates the equivalent electrical circuit of the used cell model [10]. Based on this equivalent circuit, we can model the current-voltage characteristics (I-V) of a photovoltaic generator, which is composed of N_p branches associated in parallel and each branch contains N_s cells connected in series, by (1) [10].

$$I_{pv} = N_p I_{ph} - N_p I_0 \left[exp\left(\frac{q(V_{pv} + (N_S/N_p)R_S I_{pv})}{N_S AKT}\right) - 1\right] - \frac{V_{pv} + (N_S/N_p)R_S I_{pv}}{(N_S/N_p)R_{sh}} \quad (1)$$

Where I_{pv} and V_{pv} are the PV array output current and voltage, I_{ph} is the PV cell photo-current (A), I_o is the reverse saturation current (A), q is the electron charge ($1,602\times10^{-19}$ C), A is the diode ideality factor, K is the Boltzmann constant (1.38×10^{-23} J/K) and T is the cell temperature in Kelvin (k). The photocurrent I_{ph} and the reverse saturation current I_o of the PV cell are given by (2) and (3).

$$I_{ph} = [I_{sc} + K_i(T - T_{ref})]\frac{G}{G_{ref}} \quad (2)$$

$$I_0 = I_{rs}\left(\frac{T}{T_{ref}}\right)^3 exp\left[\frac{qE_g}{AK}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (3)$$

Where: I_{sc} is the short-circuit current at nominal conditions of temperature and solar irradiation (T_{ref} = 298.55 °K et G_{ref} = 1000 W/m^2), K_i is the short-circuit current temperature coefficient in A/°K, E_g is the band-gap energy of the solar cell semiconductor and I_{rs} is the saturation current at the nominal temperature. The PV module considered in this work is Sharp ND-240QCJ, Table 1 summarizes its electrical characteristics at standard test conditions.

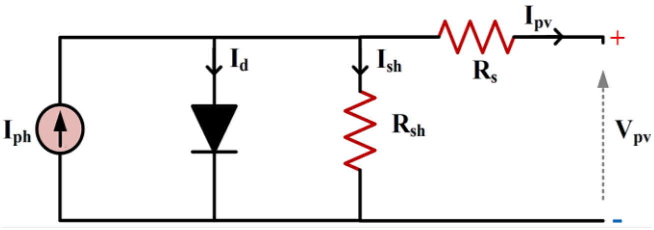

Figure 2. Equivalent circuit of PV cell

Table 1. Electrical parameters of ND-240QCJ PV module

Parameter	Values	Parameter	Values
Maximum power at STC (P_{max})	240 W	Short circuit current (I_{sc})	8.75 A
Cell serial modules (N_s)	60	Maximum power current (I_{pm})	8.19 A
Open circuit voltage (V_{oc})	37.5 V	Temperature coefficient (I_{sc}) K_i	0.053%/°C
Maximum power voltage (V_{pm})	29.3 V	Temperature coefficient (V_{oc}) K_v	-0.36%/°C

2.2. Modeling of wind system

The wind subsystem consists of a wind turbine coupled directly to a permanent magnet synchronous generator (PMSG) which converts the mechanical energy generated by the turbine into electrical energy, an AC/DC rectifier to convert the AC voltage to DC voltage, and a DC/DC boost converter to achieve the desired output voltage and power thanks to an MPPT control [12], [20]. The mechanical power P_m generated by a wind turbine can be expressed by (4) [1].

$$P_m = \frac{1}{2}\rho\, S\, C_p(\lambda,\beta)\, V_w{}^3 \tag{4}$$

Where: V_w is the wind speed (m/s), ρ is the air density (Kg/m^3), S is the rotor blade swept area, and C_p is the power coefficient describes the extraction efficiency of the wind turbine and expressed as a function of the tip speed ratio λ and blade pitch angle β by [1].

$$C_p(\lambda,\beta) = C_1\left(C_2\frac{1}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \tag{5}$$

Where, as in (6) and (7).

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \tag{6}$$

$$\lambda = \frac{\omega_r R}{V_{wind}} \tag{7}$$

The values of the coefficients C_1 to C_6 are: C_1 = 0.5176, C_2 = 116, C_3 = 0.4, C_4 = 5, C_5 = 21 and C_6 = 0.0068. R is the wind turbine rotor radius in meters (m) and ω_r is the wind turbine rotor speed. The mechanical torque Tm applied to the electrical generator is expressed by (8).

$$T_m = \frac{P_m}{\omega_r} = \frac{1}{2}\rho\pi R^3\frac{C_p(\lambda,\beta)}{\lambda}V_w{}^2 \tag{8}$$

Table 2 summarizes the technical parameters of the wind turbine and the PMSG generator used in this study.

Table 2. Parameters of wind turbine and PMSG

The wind turbine		PMSG generator	
Parameter	Values	Parameter	Values
Nominal mechanical output power	8.5 kW	Number of pole pairs	5
Base wind speed	12 m/s	Stator phase resistance	0.425 Ω
Air density ρ	1.225 kg/m^3	Armature inductance	0.000835 H
Pitch angle β	0°	Friction factor	0.001189 Nms
		Inertia constant	0.01197 kg.m^2

2.3. Modeling of storage system

In a hybrid energy system, an energy storage system is needed to meet the energy demand when the PV and wind sources become unable to track it due to climate changes [8]. The principle is to store the surplus energy generated by the PV and wind systems as electrochemical energy and recover it as electrical energy when the energy produced by the two sources is insufficient to ensure the electrical load needs. There are several types of batteries namely, lead-acid, nickel-cadmium, and lithium-ion. In this work, we propose to use Li-ion batteries [10] which are highly recommended and preferable over other batteries because they have high energy density, high operating voltage, low electrical losses, and long life (up to 20 years). Figure 3 shows the equivalent circuit of the proposed non-linear model [21]. From this equivalent circuit, the battery voltage V_{bat} (V) is given by [22].

$$V_{bat} = E - R_{int}.|I_{bat}| \tag{9}$$

Where I_{bat} is the battery current (A) and R_{int} is the internal resistance (Ω). The controlled voltage source E is expressed as a function of the battery operating mode, charging or discharging, and its actual state of charge (SOC). It is given by (10) and (11) [23].

$$E_{discharge} = E_0 - \frac{K.Q}{Q-q}.i^* - \frac{K.Q}{Q-q}.q + A.exp(-B.q) \tag{10}$$

$$E_{charge} = E_0 - \frac{K.Q}{0.1Q-q}.i^* - \frac{K.Q}{Q-q}.q + A.exp(-B.q) \tag{11}$$

The battery state of charge (SOC) is the ratio between the current capacity of the battery q and its maximum capacity Q, it is expressed as a percentage (%) by (12) [17].

$$SOC = 100\left(1 - \frac{\int_0^t I_{bat}.dt}{Q}\right) \tag{12}$$

Where E_0 is the battery constant voltage (V); K is the polarization constant $(Ah)^{-1}$; Q is the maximum battery capacity (Ah); $q = \int_0^t I_{bat}.dt$ is the actual battery charge (Ah); i^* is the low-frequency current (A); A is the exponential voltage (V); and B is the exponential capacity $(Ah)^{-1}$. For better use of the storage system, the SOC must be limited between two predefined levels, $SOC_{min} \leq SOC \leq SOC_{max}$, to avoid overcharging or deep discharging of the batteries. For battery operating mode control, charging or discharging, and DC bus voltage regulation, we added a buck-boost converter to the storage system [24].

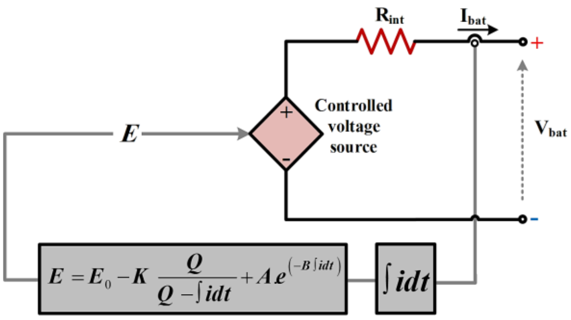

Figure 3. Non-linear battery model

2.4. Boost converter modeling

To ensure the adaptation between the sources and the electrical loads, thus the optimization of their efficiency through an MPPT control, a boost converter is used [9], [12], [17]. It is considered the most efficient and appropriate solution for photovoltaic and wind energy conversion chains, because it operates in DC current mode and allows converting a low input voltage to a higher output voltage and therefore extract as much power as possible from the generators. Figure 4 illustrates the equivalent circuit of the boost converter [25].

From this circuit, we can deduce the relationship between the input voltage V_{in} (output voltage of PV or wind generators) and the converter output voltage V_{out}, which is written as (13) [1].

$$V_{out} = \frac{V_{in}}{1-D} \tag{13}$$

The mathematical model of the boost converter depends on the duty cycle D applied to the switching device Q, which can be closed if D = 1 or open for D = 0. This model is expressed by (14) and (15) [12].

$$\frac{di_L}{dt} = \frac{1}{L}\left[V_{in} - V_{out}(1-D)\right] \tag{14}$$

$$\frac{dV_{out}}{dt} = \frac{1}{C}\left[i_L(1-D) - i_{load}\right] \tag{15}$$

Where D is the duty cycle (D_{pv} or D_{Wind}); i_L is the inductor current; and i_{load} is the load current.

2.5. Buck-boost converter modeling

In a stand-alone hybrid energy system with storage, a bidirectional DC/DC converter is used as an adaptation interface between the batteries and the system's DC bus [9], [17]. This adaptation allows both to control the charge and discharge of the storage system and to regulate the DC bus voltage to a constant voltage whatever the operating modes and conditions. All this in order, on the one hand, to optimize the batteries operating and protect their lifespan, and on the other hand, to avoid dangerous overvoltage and undervoltage in the bus that could damage the sources, loads, and power converters. Figure 5 illustrates the equivalent circuit of the used buck-boost converter [10]. The bidirectional converter dynamics model is expressed by (16) and (17) [24], [26].

$$\frac{di_{bat}}{dt} = -\left(\frac{1-D}{L}\right)V_{bus} + D\,\frac{V_{bat}}{L} \tag{16}$$

$$\frac{dV_{bus}}{dt} = \left(\frac{1-D}{C}\right)i_{bat} - \frac{i_{bus}}{C} \tag{17}$$

Where i_{bat} is the battery current (A); V_{bus} is the DC link voltage (V); V_{bat} is the battery voltage (V); i_{bus} is the bus DC current; and D is the duty cycle control (U_{Q1} or U_{Q2}).

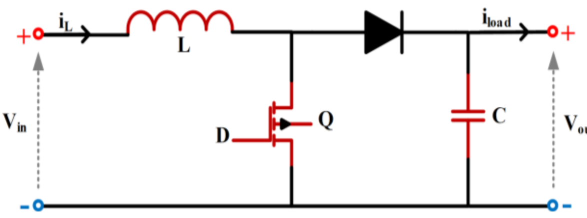

Figure 4. Equivalent boost converter circuit

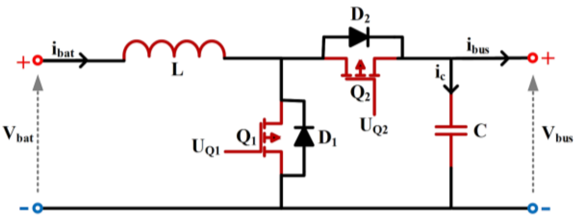

Figure 5. Equivalent buck-boost converter circuit

3. ENERGY MANAGEMENT SYSTEM

In the proposed PV/wind/batteries hybrid system, the PV and wind generators are considered as main energy sources, supplying the electrical load, and charging the storage batteries with surplus energy. They operate either in single-source or bi-source mode according to the requested load. When both PV and wind systems cannot meet the energy demand due to climate changes (solar irradiation, temperature, and wind speed), batteries act as a backup source to supply the load with stored energy. The load is supplied via a multidirectional DC bus, which allows thanks to switches to manage the energy flow direction between different sources and the electrical load. In the objective of ensuring a continuous power supply and a better exploitation of the system's energy resources, we have developed an energy flow management strategy via the multidirectional DC bus. A battery system controller is also offered to manage their operating modes, to optimize their use, and regulate the DC bus voltage through the buck-boost bidirectional converter.

3.1. System energy flow management

Based on the studied hybrid system structure and the exploited energy sources, we chose to use a hierarchical management strategy in an algorithm form based on the system power balance. The orientation of system energy flow is based on the power level demanded by the load and the power level generated by both PV and wind subsystems. Thanks to the control of the multidirectional DC bus switches, the system can be configured in either single-source or multi-source mode. For the single-source mode, the load is supplied only by one of the two sources (PV or wind) depending on the requested power, and the surplus energy is stored in the batteries. For the multi-source mode, in the case where the requested load power is greater than the power produced by the two subsystems individually, the two sources are used simultaneously to supply the load and the excess energy will be stored in the batteries. Moreover, in case the demand becomes unbearable by both sources, the batteries act as a backup source to meet the needs and ensure the system's autonomy.

Figure 6 illustrates the proposed system management strategy; it depends on the power requested by the load (P_{load}) and power produced by both PV and wind generators (P_{pv} and P_{wind}). The control orders provided by this strategy allow acting on the multidirectional bus switches to direct the system energy flow to supply the load and charge or discharge the batteries.

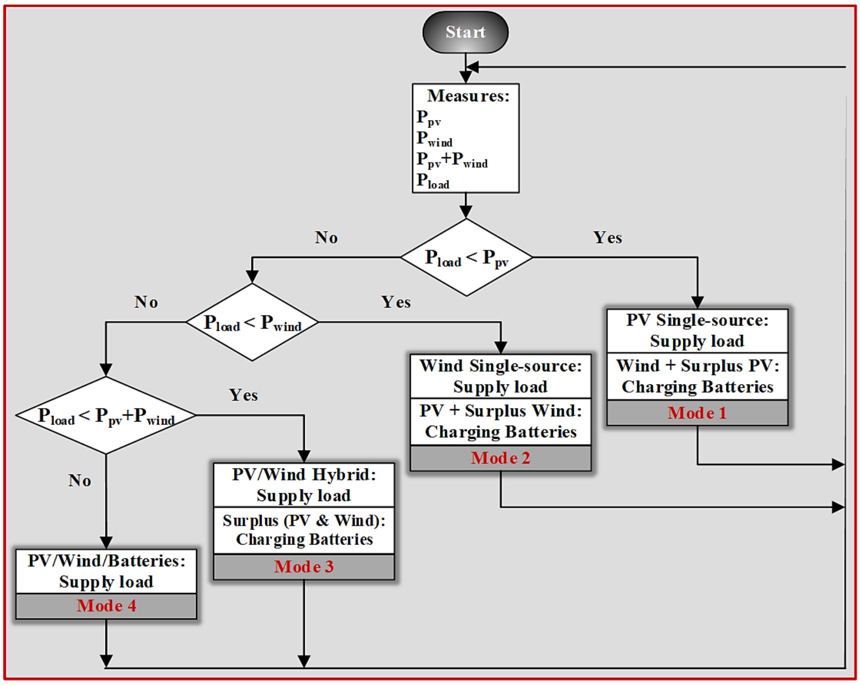

Figure 6. Proposed system energy management strategy

According to this strategy, 4 system operating modes can be configured:

- Mode 1 (PV single-source): In this case, where the load power is lower than the PV generator ($P_{load} < P_{pv}$), the load is supplied only by the PV subsystem, and the surplus energy produced by this latter and that of the wind generator is oriented towards the storage system charging.
- Mode 2 (wind single-source): In this case, where the load power is greater than the PV generator and lower than the wind generator ($P_{pv} < P_{load} < P_{wind}$), the load is supplied only by the wind subsystem, and the excess energy supplied by both PV and wind generators will be stored in the batteries.
- Mode 3 (PV/wind hybrid-source): In this case, where the load power is lower than the sum of the two PV and wind generators ($P_{load} < P_{pv} + P_{wind}$), the load will be supplied by both sources simultaneously, and the surplus energy is oriented towards the storage system charging.
- Mode 4 (PV/wind/batteries hybrid system): In this case, where the load power is greater than the sum of the two PV and wind generators ($P_{load} > P_{pv} + P_{wind}$), the load will be supplied by both sources and the use of the energy stored in the batteries to meet the demand requirements.

To realize the proposed energy management strategy, we chose to use the fuzzy logic technique because of its simplicity and high efficiency. Figure 7 shows the developed fuzzy logic controller. This controller is based on the Mamdani’s fuzzy inference with the Min-Max method for fuzzification and the center of gravity method for defuzzification [17], [18]. The controller has three inputs: (P_{pv} - P_{load}), (P_{wind} - P_{load}), and (P_{sr} - P_{load}), and only one output corresponds to the operating mode (MF). Figures 8(a)-8(c) show the membership functions for the controller input variables, while Figure 8(d) shows those for the output variable. The inputs have two membership functions: negative (N) and positive (P). The output has four functions: operating mode 1 (MF1), operating mode 2 (MF2), operating mode 3 (MF3), and operating mode 4 (MF4). According to the proposed management algorithm, and in order to configure all possible operating modes of the system, a rules list is defined to link the output to the inputs. Based on these rules, the controller generates the appropriate control signal to configure the correct operating mode, through the multidirectional DC bus switches.

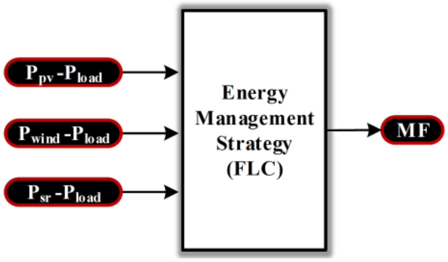

Figure 7. Fuzzy logic controller

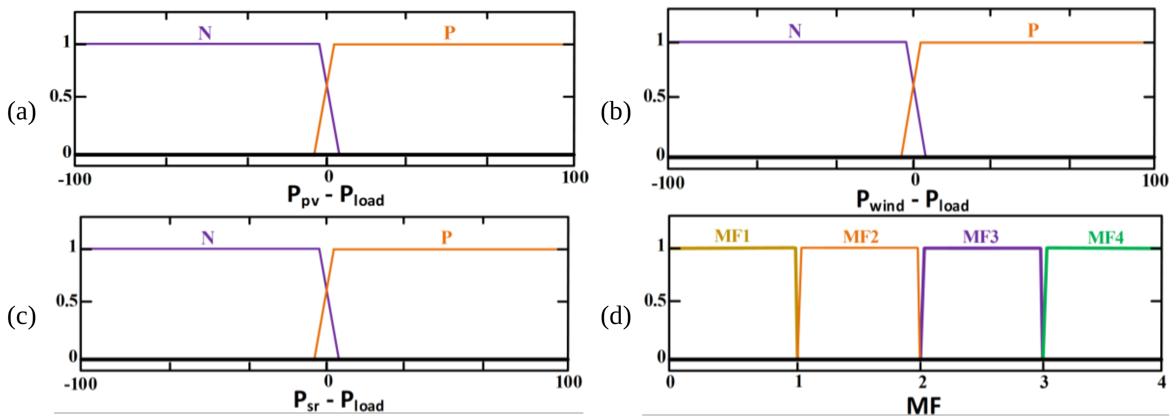

Figure 8. Membership functions for: (a) input P_{pv}-P_{load}, (b) input P_{wind}-P_{load}, (c) input P_{sr}-P_{load}, and (d) output MF

3.2. Storage system management

Given the economic and energetic impact of storage batteries on the design of a stand-alone hybrid energy system, and their importance to guarantee system autonomy and energy security, a controller is needed to manage and optimize their operation. According to the proposed energy management strategy, batteries are used only as a backup source, which reduces their charge/discharge rate, thereby increasing their efficiency and extending their lifespan.

The proposed storage system controller has two parts. The first includes an algorithm to control charge and discharge modes, keeping the battery state of charge within allowable limits. The second part has a DC bus voltage control loop to maintain it at a reference value whatever the system operating mode. This management is done via the switches Q_1 and Q_2 of the buck-boost bidirectional converter, two modes can be configured, buck mode (charge) or boost mode (discharge), depending on the operating mode defined by the system energy management strategy [24]. During buck mode, the switch Q_1 is open, Q_2 is closed and the batteries are charging. While, in boost mode, the switch Q_1 is closed, Q_2 is open and therefore the batteries are discharging. Figure 9 illustrates the principle of storage system management.

Figure 10 presents the proposed algorithm to ensure that the batteries state of charge is limited between two predefined levels, SOC_{min} and SOC_{max}, this allows to avoid an overcharging or deep discharge of the batteries and consequently to increase their efficiency and their lifetime. This algorithm is based on the operating mode defined by the system management strategy, it allows to continuously supervise the level of the batteries state of charge and compare it with reference levels SOC_{min} and SOC_{max}, which are chosen in our study equal 20% and 80% respectively [17].

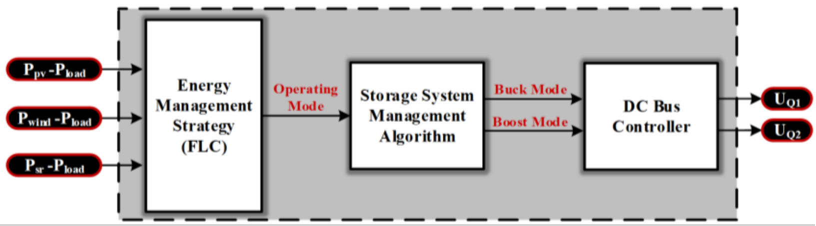

Figure 9. Proposed storage system management

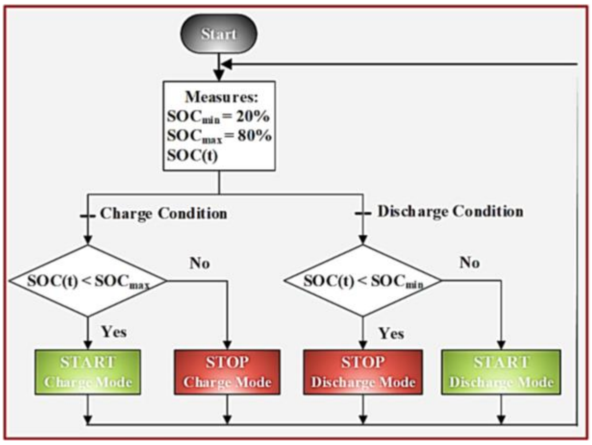

Figure 10. Storage system management algorithm

Based on the batteries system and its bidirectional converter, we can regulate the DC bus voltage V_{bus} at a constant reference voltage V_{ref}, whatever the operating modes and conditions. Figure 11 shows the proposed controller synoptic diagram which depends on the storage system operating mode (buck or boost). If the mode defined by the batteries management algorithm is the charging mode (buck), the controller takes in consideration the batteries output voltage V_{bat} to maintain it at the reference voltage V_{ref}. Otherwise, the controller is based on the output voltage of the bidirectional converter V_{bus} because we are in discharge mode (boost). To obtain the control laws U_{Q1} and U_{Q2} which control the switches Q_1 (for buck mode) and Q_2 (for boost mode) of the bidirectional converter, we used two control loops based on two proportional-integral regulators PI_Buck and PI_Boost with a PWM signal generator [26]. The control laws are given by (18) and (19) [26].

$$U_{Q1}(t) = K_{P_{buck}}\left[V_{ref} - V_{bat}(t)\right] + K_{I_{buck}} \int \left[V_{ref} - V_{bat}(t)\right] dt \tag{18}$$

$$U_{Q2}(t) = K_{P_{boost}}\left[V_{ref} - V_{bus}(t)\right] + K_{I_{boost}} \int \left[V_{ref} - V_{bus}(t)\right] dt \tag{19}$$

Where $K_{P_{buck}}$, $K_{I_{buck}}$ and $K_{P_{boost}}$, $K_{I_{boost}}$ are the controller PI_Buck and PI_Boost gains respectively.

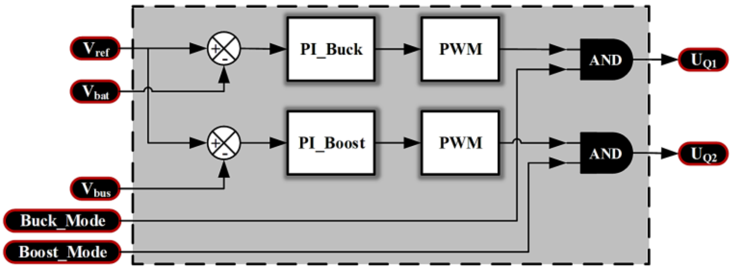

Figure 11. Proposed DC bus controller

4. SIMULATION RESULTS AND DISCUSSION

In this work, a simulation of a standalone hybrid energy system is performed in the MATLAB/Simulink software, using the parameters of the various elements modeled previously. This system consists of a wind generator based on a turbine of 8.5 kW, a photovoltaic system contains 16 PV panels of 240 W and a storage system contains 20 lithium-ion batteries with a capacity of 100 Ah and voltage of 48 V. In the objective of optimizing the proposed PV/wind/batteries system performance, we have developed a MPPT controller based on robust techniques to improve the power generated by both PV and wind sources [27]. Also, an energy management strategy of the complete system has been designed to manage the energy flow between different sources and the electrical load. In addition, a controller is developed to control the battery system operating modes with a control of its state of charge SOC and the regulation of DC bus voltage at a reference voltage fixed to 500 V. For a better verification and analysis study of the proposed strategies and controls, the simulations are carried out under varying operating conditions.

Figure 12 illustrates simulation results for the energy flow management between the PV subsystem, the wind subsystem, and the batteries according to the following operating modes and climatic conditions:

- Case 1 (t = 0 s to t = 1 s): load of 2000 W, irradiation of 1000 W/m^2, and wind speed of 12 m/s.
- Case 2 (t = 1 s to t = 2 s): load of 3150 W, irradiation of 800 W/m^2, and wind speed of 10 m/s.
- Case 3 (t = 2 s to t = 3 s): load of 3500 W, irradiation of 600 W/m^2, and wind speed of 8 m/s.
- Case 4 (t = 3 s to t = 4 s): load of 1.5 kW, irradiation of 1000 W/m^2, and wind speed of 12 m/s.

These results show the good hierarchical system management to ensure the power demanded by the load. For case 1, where the load power is less than the PV power, the PV generator supply the load and the surplus with the wind subsystem power charge the batteries. In case 2, where the load power is greater than the PV power and less than that of the wind, the demand is provided by the wind subsystem. The surplus energy and that produced by the PV subsystem are stored in the batteries. In case 3, where the load power is greater than the two powers generated individually by both sources (PV and wind) and lower than their sum, the both subsystems supplies the load and the excess energy is used to charge the batteries. In case 4, where the total power generated by PV/wind hybrid system is less than the load power, the storage system intervenes as a backup source to meet the requested power.

Figures 13 and 14 show the batteries state of charge (which is initialized in this simulation at the level of 50%) and current, respectively. In cases 1, 2, and 3, the batteries are in charging mode and the SOC level depends on the energy amount injected into the storage system by the PV and wind sources. In case 4, the batteries are discharged resulting a SOC level decrease to inject the missing energy into the DC bus to meet 100% the electrical load needs. Figure 15 shows the DC bus voltage V_{bus} which is maintained at a reference voltage of 500 V. The simulation results present the good efficiency of the controller used to regulate this voltage following changes in the system operating mode. Under the various controls applied to the multidirectional DC bus switches, the DC bus can be maintained at its reference value with a good dynamic response.

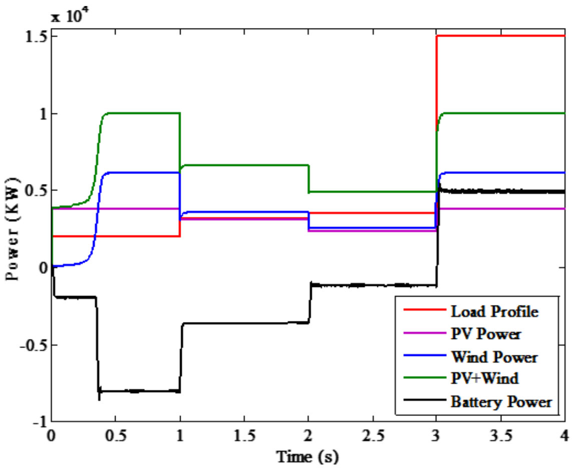

Figure 12. PV, wind, battery, and load power

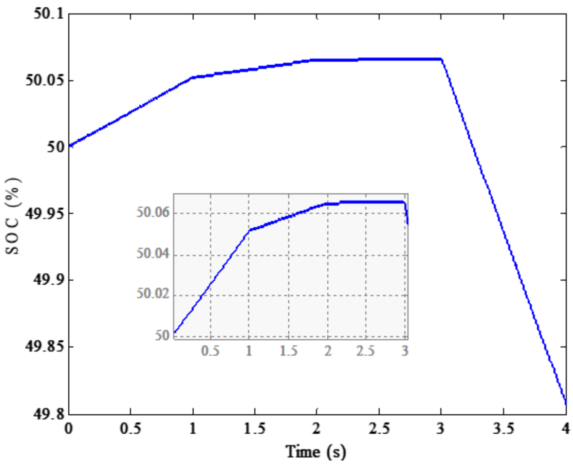

Figure 13. Batteries state of charge SOC (%)

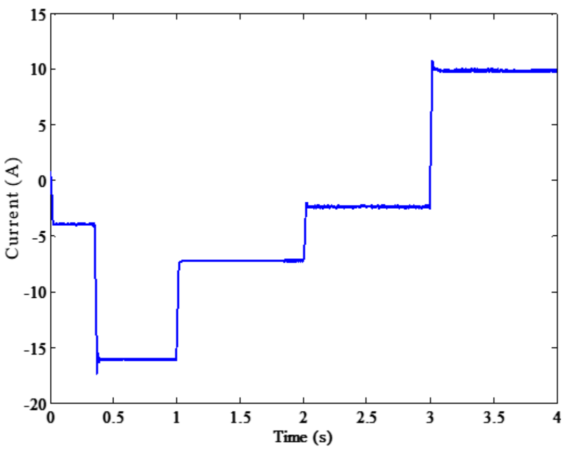

Figure 14. Batteries current (I_{bat})

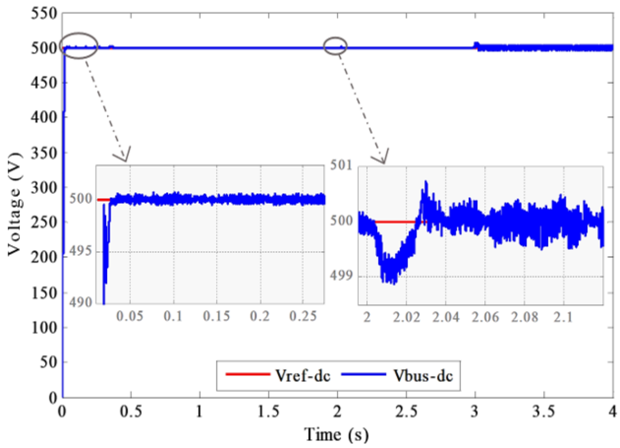

Figure 15. DC bus voltage (V_{bus})

5. CONCLUSION

In this work, an energy management strategy has been proposed to optimize the use of a standalone PV/wind/battery hybrid system in isolated areas. The purpose of this strategy is to manage the power flow between the sources and the load, and also to control the system storage batteries. A fuzzy logic-based controller has been developed to supervise the system power flow through the multidirectional DC bus. This controller is based on a hierarchical algorithm to ensure the electrical load according to the power generated by the sources and the power requested by the load. In addition, a controller has been proposed to manage the storage system in order to control the batteries operating modes, also to supervise their state of charge (SOC) and to regulate the DC bus voltage. The simulation results have shown that the proposed strategy allows, whatever the weather conditions and the power required by the load, to ensure an optimal hierarchical operation between the different sources of the system with good efficiency and a good dynamic response under the operating mode changes. And as a perspective of our work, we are considering to integrate a hybrid storage system that combines two storage types with another optimal system energy management strategy.

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BIOGRAPHIES OF AUTHORS

Dr. Otmane Zebraoui presently a professor and researcher at the Moroccan School of Engineering Sciences in Rabat, Morocco. He obtained his Ph.D. in Electrical Engineering and Renewable Energies from the Sciences and Technics Faculty at Hassan 1st University, Settat, Morocco. His expertise lies in the modeling, controlling, and optimizing hybrid energy systems, encompassing PV, wind, and battery technologies. He can be contacted at email: otmanezebraoui@gmail.com.

Dr. Mostafa Bouzi is a research professor in Electrical Engineering Department at Science and technology faculty, Hassan 1st University. He received the Engineering degree in Electrical Engineering, from Engineer school of Lille in France, obtained the Ph.D. degree in Photovoltaic System Control at Hassan 1st University and got his habilitation to supervise research at Hassan 1st University. His current research activities are in the fields of electrical systems, renewable energy conversion systems, and nonlinear control system. He can be contacted at email: mostafabouzi@yahoo.fr.

Dr. Badr Nasiri earned his Ph.D. in electronics and telecommunications from the Sciences and Technics Faculty at Hassan 1st University in Settat, Morocco. Presently, he holds the associate professor of Electronics position at the Faculty of Science, University Moulay Ismail, Meknes, Morocco. He is actively engaged in developing and applying passive planar circuits utilizing metamaterials. He can be contacted at email: b.nasiri@uhp.ac.ma.