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Energy management based fuzzy logic controller of hybrid system wind/photovoltaic/diesel with storage battery

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ABSTRACT

Hybrid renewable energy systems (HRES) are attractive configurations used for different applications and especially in standalone power generation systems as electrification, water pumping, and telecommunications. Considering the multitude of sources, energy management control (EMC) will be necessary. In this paper, supervision of hybrid Wind/Photovoltaic/Diesel system with battery storage is presented. The power balance of the suggested system is made on an intelligent supervisor based on fuzzy logic control (FLC). It is simple, easy and makes it possible to determine the various operating processes of the hybrid system according to the weather conditions. The decisions of criterion required by this method are presented. The study was implemented under Matlab/Simulink and an application is made for Bejaia a site in the coastal region of Algeria. The obtained results are presented and show the feasibility of the proposed control system.

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Introduction

Due to the different advantages of PV/Wind energy conversion systems, a great attention has been focused on them. The best advantage of these systems is not only to provide continuous energy whatever the variations of the load and of the weather conditions but to generate different sources in an intelligent manner that allows satisfying the load demand and to maintain the batteries charged. Various architectures of the hybrid energy system have been proposed with different power management controls (PMC). Some of them are based on logical states and others on intelligent algorithms. The lathers are more interesting especially for standalone applications (remote control).

A number of literature have been reported to investigate PMCs. The applications are focused on electrification and smart grids [1–3], water pumping [4], telecommunications [5]. In general, in all the papers, management is always based on power balance. Some author have proposed diverse methods of power management control, in Refs. [6–8] fuzzy logic control, in Ref. [9] flatness Based Control, in Ref. [10] frequency deviation control and in Refs. [4–11] control with microcontroller. Modeling of the different sources is based on well-known mathematical models [12–33]. FLC has been used for Maximum Power Point Tracking (MPPT) of solar PV [34,35] and frequency regulation [36,37], for controlling batteries' output charger current [38], improvement in wind power prediction accuracy [39], and for voltage control of the hybrid energy

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Nomenclature

C_p	Power
G	Solar radiation, W/m^2
I_{pv}	Output-terminal current, A
I_{ph}	Diode-current, A
I_{Rsh}	Shunt-leakage current, A
I_{sc}	Short circuit current, A
P_{mpp}	Maximum power point, W
P_{PV}	Photovoltaic power, W
R_s	Series resistance, Ω
R_{sh}	Shunt resistance, Ω
T_c	Temperature cells, K
T_{cSTC}	Reference temperature of the PV cell, K
V_{mpp}	Maximum voltage at PPM, V
V_{oc}	Open circuit voltage, V
K_1, K_2, K_3, m	Coefficients
T_{wind}	Wind torque, N m
T_{mec}	Mechanics torque, N m
R	Radius of the rotor, m
S	Area swept by the rotor blades, m^2
V_{wind}	Wind speed, m/s
V_{bat}	Battery voltage, V
Q_0	Capacity of the battery, Ah
E_0	Ideal voltage of the charged battery, V
K	Constant that depends on the battery
R_b	Internal resistance of the battery, Ω
I_b	Discharge current, A
I_d, I_q	Stator currents direct and quadratic, A
V_d, V_q	Stator voltage direct and quadratic, V
L_c	Inductance of each stator phase, H
R_C	Resistance of each stator phase, Ω
T_{em}	Electromagnetic torque, N m
P	Power, W
e_d, e_q	Magneto motor force direct and quadratic, V
K_{pv}	Control signal of the switch for the photovoltaic generator
K_{wind}	Control signal of the switch for the wind generator
K_{dies}	Control signal of the switch for the diesel generator
P_{pv}	Photovoltaic power, W
P_{wind}	Wind power, W
P_{die}	Diesel power, W
V_{dc}	DC voltage, V
$V_{dc\text{-}ref}$	DC voltage reference,V

Greek letters

α_{sc}	Temperature coefficient of short-current, A/K
β_{oc}	Voltage temperature coefficient, V/K
ρ_{air}	Air density
ϕf	Amplitude of flux of permanent magnets
ω	Angular speed, rad/s
λ	Tip speed ratio
α_1	Duty cycle
α_2	Duty cycle
α_3	Duty cycle

Abbreviations

AC	Alternate current
DC	Direct current
EMC	Power management control
HPS	Hybrid power system
PMSM	Permanent magnet synchronous motor
PV	Photovoltaic panels
PMSG	Permanent magnet Synchronous generator
PWM	Pulse width modulation
SOC	Battery charge status
SOC_{min}	Minimum battery state of charge
SOC_{max}	Maximum battery state of charge
STC	Standard tests conditions
FLC	Fuzzy logic Control
LOW	Low
MED	Medium
MAX	Maximum
HIGH	High

system (wind/battery) [40,41], In this article Fuzzy Logic Control (FLC) has been opted as it is a flexible tool with rules based on human knowledge and experience that can handle unpredictable variables or uncertainties. FLC can be applied to complex systems such as hybrid energy systems with different types of inaccurate inputs, variables and perturbations, especially if power is supplied by renewable energy sources is consumed by variable and unpredictable loads.

Several publications have also been published on using FLC for energy management of hybrid energy systems and storage batteries [41–47]. In Refs. [42,43], FLC has been used to provide a proper split in power between solar PV, wind and storage batteries according to a pre-defined rule. The SOC of storage batteries in a hybrid micro grid was controlled by a FLC in Ref. [44] to improve the performance of the hybrid generation system with smaller energy capacity of storage batteries [45]. Proposes an efficient controller of Fuzzy Logic Controller (FLC) predetermined power organization for accurate source selection in the right timing for powering telecommunication loads and managing the entire hybrid power system. A fuzzy logic-based controller to be used for the Battery SOC control of the designed hybrid system hybrid solar photovoltaic and wind power system in Battery management for stand-alone applications [46] and in Ref. [47] controller based on fuzzy logic to prevent the battery state of charge and charging/discharging power from exceeding their limits regardless of variations in load and intermittent power of renewable source.

In this paper, an intelligent power management control of a hybrid Wind/Photovoltaic/Diesel system with battery storage is presented. Which is based on fuzzy logic control (FLC). It is simple, easy and enables in the first part, to determine the variant operating processes of the hybrid system according to the weather conditions and thus determine the power supplied for each source facilely and rapidly compared to classical strategies based on logical states. And in the second part, it

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maintains the state of charge of the battery bank to prevent blackout and to extend the life time of batteries.). The model has been implemented under Matlab/Simulink. An application is carried out for the Bejaia site Algeria which is a coastal region with an interesting complementary solar and wind sources. The obtained results are presented and depict the feasibility of the proposed system which will be interesting in several applications such as telecommunications, electrification, pumping of water.

Description of the studied system

The hybrid energy system studied in our work contains two renewable energy sources (photovoltaic and wind generator), a backup generator (diesel) and a storage system. The studied configuration of the system is architecture with a DC bus. The PMC based on fuzzy logic control is in first place to satisfy the load power demand and in second place to maintain the state of charge of the battery bank to prevent blackout and to extend the life time batteries regardless the variations in solar irradiance and wind speeds. The topology of the hybrid system under consideration in this paper is represented in Fig. 1.

Analysis of the solar and wind potential available in Bejaia

The Bejaia meteorological service supplied us with a complete file of wind speed and solar irradiance recorded monthly at the weather station of Bejaia in the coastal region of Algeria for a ten-year period from 1998 to 2007 (Fig. 2).

Bejaia region has a great solar potential, which is characterized by a hot summer season (June–September). Daily average monthly values of global irradiance on horizontal plane stored in the 1998–2008 period are shown in Fig. 3. Which are significant for the period (April–September) compared to the other months of the year. The wind potential is also very interesting according to the wind speed data stored at the Bejaia weather station over the period 1998–2008. The monthly average speed is shown in Fig. 3. It can be seen that our site has also considerable wind potential with an annual average wind speed of about 3.975 m/s. Given their complementary nature, it is concluded that the coupling of a photovoltaic system and wind turbine is very interesting to ensure the production of electrical energy throughout the year. The Bejaia site is favorable for the installation of a hybrid system (Fig. 3).

Modeling of the proposed system

The studied configuration of the system is the architecture with the DC bus which is shown in Fig. 4. The principle of control applied is to monitor the renewable energy voltage sources to be equal to the voltage at the DC bus, regardless the variations of solar irradiance and wind speed.

Model of PV array

Various mathematical models of photovoltaic generators were developed to represent their nonlinear behavior which results from the semiconductor junctions which are at the base of their realization. In this work, the following model (Fig. 5) is chosen [12,13]:

The current (I_{pv}) of the photovoltaic cell under standard operating conditions is given by Eq. (1) according to Fig. 5:

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

where: I_{ph} represents the photo-current, it depends on the irradiance and temperature, I_d: Polarization of the PN Junction Current and I_{Rsh} : Current in the Resistor R_{sh}.

The current expression of the solar cell is given by:

$$I_{pv} = I_{sc}\{1 - K_1[exp\ (K_2.V_{mpv} - 1)]\} \tag{2}$$

where K_1, K_2 and m coefficients are given in Ref. [4].

$K_1 = 0.01175$

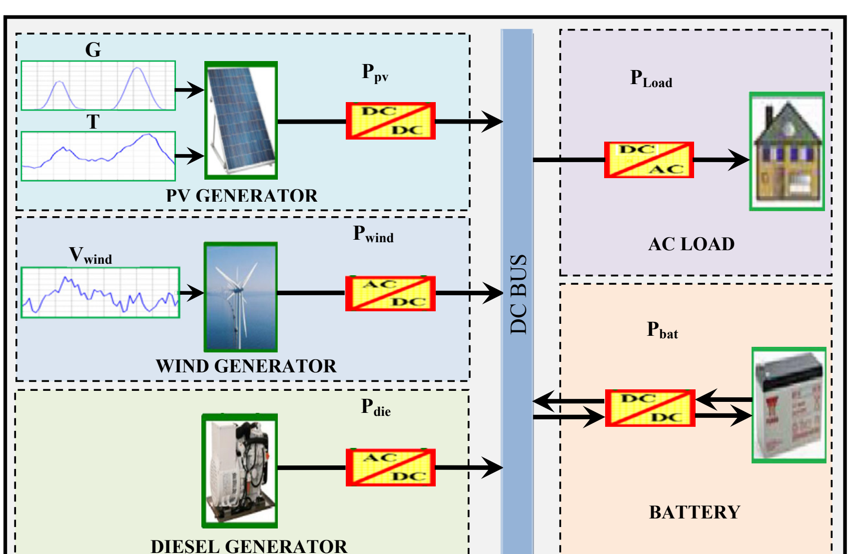

Fig. 1 – Hybrid power system description.

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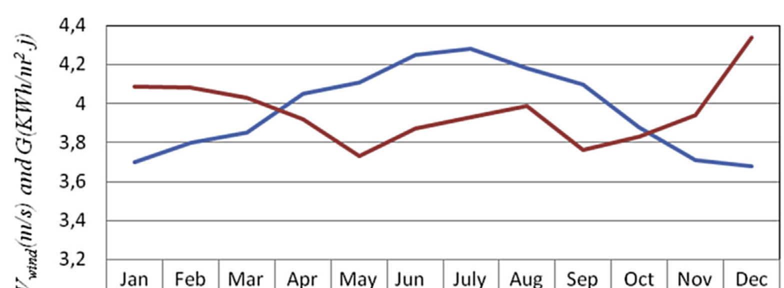
Fig. 2 – Area of Bejaia site (Algeria).



	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
G(KWh/m2.j)	3,7	3,8	3,85	4,05	4,11	4,25	4,28	4,18	4,1	3,88	3,71	3,68
Vwind(m/s)	4,09	4,08	4,03	3,92	3,73	3,87	3,93	3,99	3,76	3,83	3,94	4,34

Fig. 3 – Monthly average daily global irradiation on horizontal and wind speed from Bejaia site for ten years.

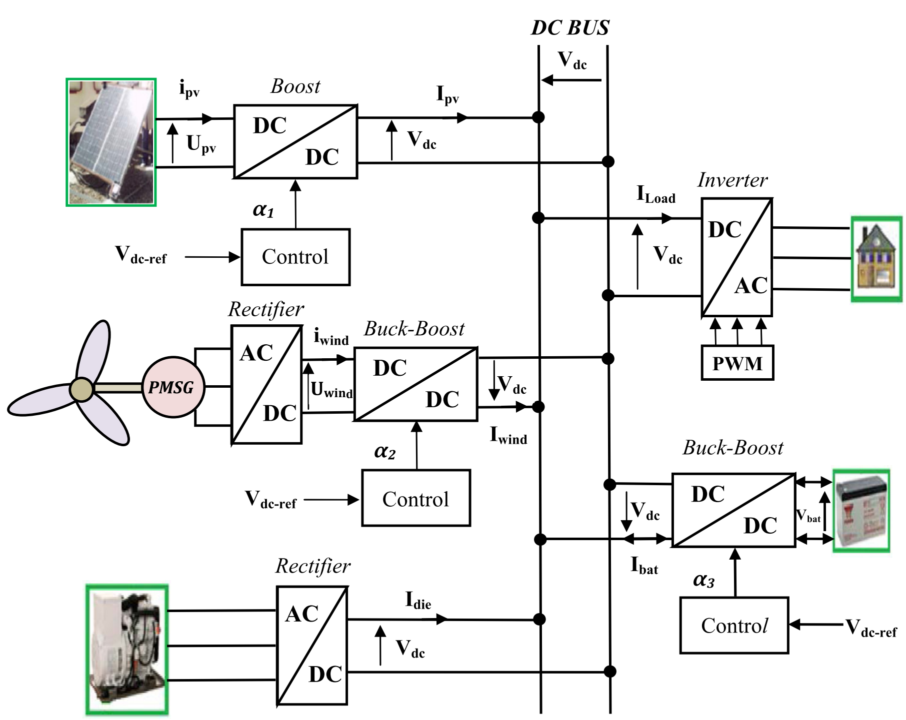


Fig. 4 – Configuration of the system studied.

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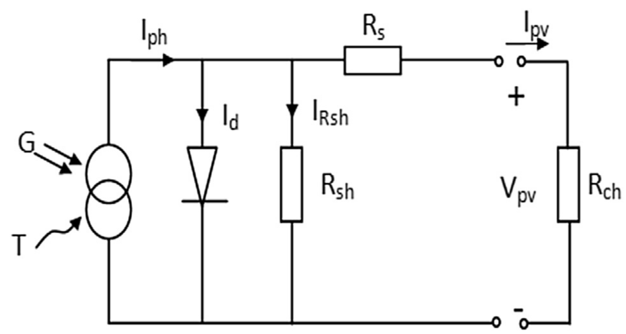


Fig. 5 – Equivalent circuit of solar cell.

$$K_2 = \frac{K_4}{V_{oc}^m} \quad (3)$$

$$K_3 = ln\left[\frac{I_{sc}(1+K_1) - I_{mpp}}{K_1 * I_{sc}}\right] \quad (4)$$

$$K_4 = \ln\left[\frac{1+K_1}{K_1}\right] \quad (5)$$

$$m = \frac{\ln\left[\frac{K_3}{K_4}\right]}{\ln\left[\frac{V_{mpp}}{V_{oc}}\right]} \quad (6)$$

Eq. (2) is only applicable at one particular irradiance level G, and at cell temperature T_c, at standard tests conditions (STC) (G_{STC} = 1000 W/m^2, T_{STC} = 25 °C). When insolation and temperature vary, the parameters change according to the following equations:

$$\Delta T_c = T_c - T_{stc} \quad (7)$$

$$\Delta I_{pv} = \alpha_{sc}\left(\frac{G}{G_{stc}}\right)\Delta T_c + \left(\frac{G}{G_{stc}} - 1\right)I_{sc,stc} \quad (8)$$

$$\Delta V_{pv} = -\beta_{oc}\Delta T_c - R_s \Delta I_{pv} \quad (9)$$

The curves power-voltage P_{pv} (V_{pv}) and current-voltage I_{pv} (V_{pv}) of the photovoltaic panel are carried out under three levels of irradiance and temperature (G = 383 W/m^2 T_c = 23.2 °C; G = 659 W/m^2 T_c = 27.5 °C; G = 880 W/m^2 T_c = 32.4 °C). From the current and power characteristics, the non-linear nature of the PV array is apparent. Thus, an MPPT algorithm must be incorporated to force the system to always operate at the maximum power point (MPP) Table 1. Shows the parameters of SUNTECH solar panel which has been used in this study.

Table 1 – PV solar SUNTECH STPO80S-12/Bb parameters [17].

Parameters	Designation	Values
P_{PV}	Photovoltaic power (W)	80 Wp
I_{mpp}	Maxi mum current at PPM (A)	4.58 A
V_{mpp}	Maximum voltage at PPM (V)	17.5 V
I_{sc}	Short circuit current (A)	4.95 A
V_{oc}	Open circuit voltage (V)	21.9 V
α_{sc}	Temperature coefficient of short-current (A/°K)	3.00 mA/°C
β_{oc}	Voltage temperature coefficient (V/°K)	−150 mV/°C

The simulation and experimental results electrical results under different solar irradiance are represented in Fig. 6.

Wind system model

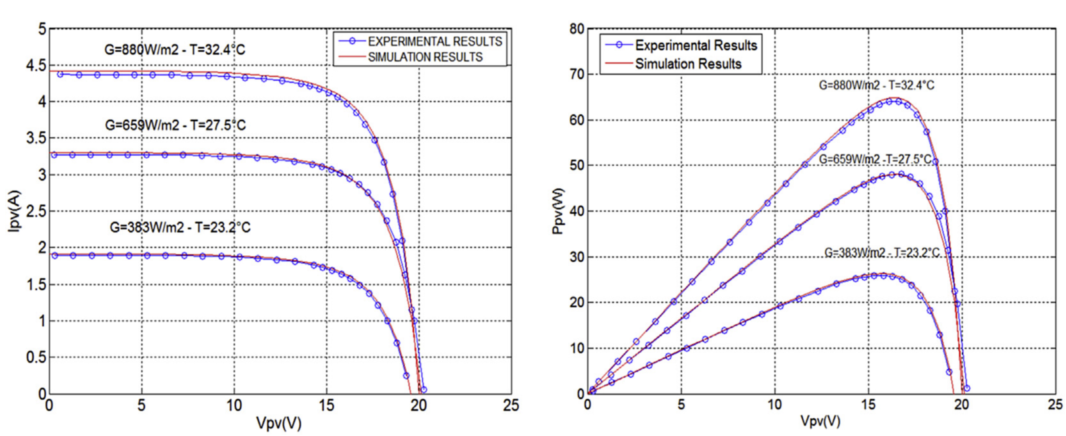
The wind generator consists of a wing which captures the kinetic energy of the wind coupled directly with a synchronous generator which delivers on a DC bus via a diode rectifier; this is the retained structure for this modeling and simulation work.

The power coefficient is [14]:

$$Cp = \frac{2 \cdot P_{wind}}{\lambda \cdot S \cdot V_{wind}^3} \quad (10)$$

The output power and the torque of the wind turbine have calculate by using the following equations below [4]:

$$P_{wind} = \frac{1}{2}Cp(\lambda) \cdot \rho \cdot S \cdot V_{wind}^3 \quad (11)$$



(a) I_{pv}-V_{pv} (b) P_{pv}-V_{pv}

Fig. 6 – Simulation and experimental electrical curves.

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$$T_{wind} = T_{mec} = \frac{1}{2}\frac{Cp(\lambda)\cdot\rho\cdot R\cdot S\cdot V_{wind}^2}{\lambda} \quad (12)$$

where: S is the area traversed by the rotor blades (m^2), ρ the air density, R is the radius of the rotor (m), V_{wind} is the wind speed (m/s), λ is the tip speed ratio.

The permanent magnet synchronous machine model used is modeled by the following equations [16,17]:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_C & -\omega L_c \\ \omega L_c & R_C \end{bmatrix} * \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L_c\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} e_d \\ e_q \end{bmatrix} \quad (13)$$

The electromagnetic torque is given by:

$$T_{em} = \frac{p}{\omega}(e_q\cdot i_q) = p\cdot\Psi_f\cdot i_q \quad (14)$$

where:

e_d, e_q: direct and quadratic magneto motive force, V.
I_d, I_q: direct and quadratic stator currents, A.
V_d, V_q: direct and quadratic stator voltage, V.
L_c: Inductance of each stator phase, H.
R_C: Resistance of each stator phase, Ω.

Storage modeling

It is based on the electrical scheme presented in Fig. 7, containing three elements: a voltage source, the internal resistance and the capacity [18,19].

$$U_{bat} = E_0 - K\cdot\frac{\int I_b dt}{Q_0} - R_b\cdot I_b \quad (15)$$

- E_0: is the empty voltage of the charged battery, V
- K: is a constant that depends on the battery.
- R_b : is the internal resistance of the battery, Ω
- I_b: is the discharge current, A

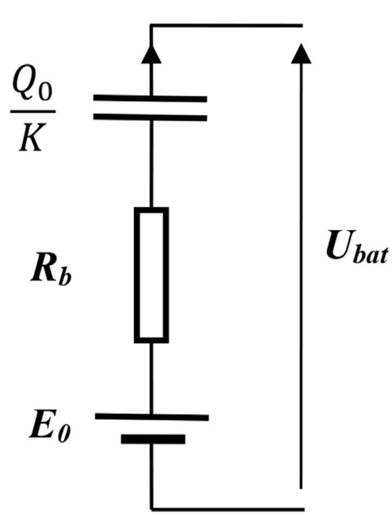

Fig. 7 – Electrical model of the battery.

- $\frac{\int I_b.dt}{Q_0}$: Indicates the discharge status of the battery.
- Q_0: Is the capacity of the battery in (Ah).

Energy management control of the hybrid energy system by fuzzy logic control

Management strategy for the autonomous standalone hybrid energy system is to satisfy the load demand under variable weather conditions and to manage the power flow while ensuring efficient operation of the different energy systems. The management strategy should primarily use the power generated by the PV and the wind system to satisfy the load demand. The principle of the fuzzy logic controller [20–33] consists in generating three control signals K_{pv}, K_{wind}, and K_{die} starting from three inputs: solar irradiation G, wind speed V_{wind} and the battery state of charge SOC.

Where: K_{pv}: Control signal of the switch of the photovoltaic generators, K_{wind}: Control signal of the switch of the wind generator and K_{die}: Control signal of the switch of the diesel generator.

Table 2 shows the rule table of fuzzy controller where the inputs of the matrix are fuzzy sets of SOC, G and V_{wind}. The output of this table is the state of the three switches K_{pv}, K_{wind} and K_{die} (Table 3).

Table 2 – Fuzzy inference inputs/outputs of fuzzy controller.

SOC	G	V_{wind}	K_{pv}	K_{wind}	K_{die}
LOW	LOW	LOW	OFF	ON	OFF
	LOW	MED	OFF	OFF	OFF
	LOW	HIGH	OFF	ON	OFF
	MED	LOW	OFF	ON	OFF
	MED	MED	OFF	OFF	OFF
	MED	HIGH	OFF	ON	OFF
	MAX	LOW	OFF	ON	OFF
	MAX	MED	OFF	OFF	OFF
	MAX	HIGH	OFF	ON	OFF
MED	LOW	LOW	OFF	ON	ON
	LOW	MED	OFF	OFF	ON
	LOW	HIGH	OFF	ON	ON
	MED	LOW	OFF	ON	ON
	MED	MED	OFF	OFF	ON
	MED	HIGH	OFF	ON	ON
	MAX	LOW	OFF	ON	ON
	MAX	MED	OFF	OFF	ON
	MAX	HIGH	OFF	ON	ON
MAX	∀G	$\forall V_{wind}$	ON	ON	ON

Table 3 – Parameter of fuzzy controller inputs.

G (W/m^2)	LOW	MED	MAX
	0–200	200–600	600–1000
V (m/s)	LOW	MED	HIGH
	0–3	3–12	12–20
SOC (%)	LOW	MED	MAX
	0–25	25–75	75–100

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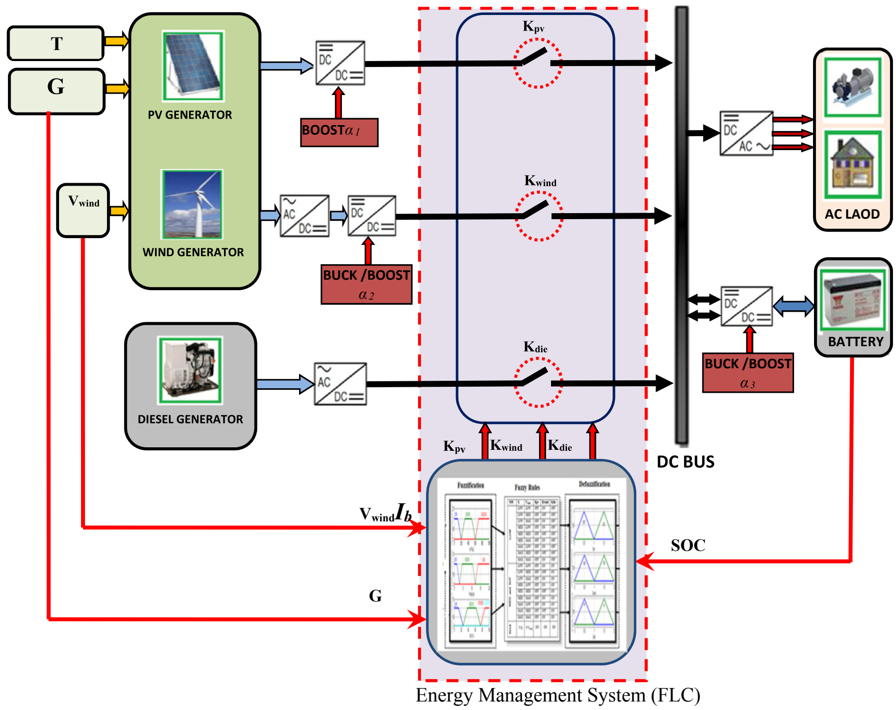

Fig. 8 – General structure of the proposed system.

Depending on the (On/Off) state of the K_{pv}, K_{wind} and K_{die} switches, it can obtained eight different modes, where the power supplied to the load is written as:

$$P_{Load}(t) + P_{bat}(t) = P_{pv}(t)*K_{pv} + P_{wind}(t)*K_{wind} + P_{die}(t)*K_{die} \quad (16)$$

where:

- $P_{bat} > 0$: When the batteries are charged.
- $P_{bat} < 0$: When the batteries are discharged.

Mode 1 (**M1**) The three sources (PV, Wind and diesel generator) supply the load, via DC/DC converter for wind and solar systems to the DC bus and via DC/AC to the AC load. In this case, the total energy is sufficient to feed the load and the excess used to charge batteries.

Mode 2 (**M2**): in this case, wind and solar energy are the main sources used. The PV (or wind) can deliver just a portion of energy, so both PV and wind contribute to charge the load. And of course, the excess is used to charge the batteries.

Mode 3 (**M3**): If the PV energy is sufficient to charge the load, the charging is entirely done by the PV. In general this mode occurs during a shiny day (summer).

Mode 4 (**M4**): In this case the PV source can be insufficient to supply load so diesel generators are used.

Mode 5 (**M5**): The wind energy is the only source, which is the case on a winter day no solar irradiance or during night with a good wind speed. So under these circumstances, it is sufficient to obtain the load energy.

Mode 6 (**M6**): This happens when wind energy is insufficient, thus the diesel generators start and make up for the energy deficit.

Mode 7 (**M7**): Only diesel generators are in use.

Mode 8 (**M8**): No sources available or no power to supply.

Table 4 – Different parameters of each subsystem.

Photovoltaic generator	Values
Power rating	400 W
Wind generator	
Power rating	600 W
Radius of the turbine	1 m
Diesel generator	
Power rating	2 KVA
Battery bank	
Capacity	4 × 100 Ah
Rated voltage	4 × 12 V
Minimum acceptable voltage level (V_{min})	4 × 11.5 V
Maximum acceptable voltage level (V_{max})	4 × 12.73 V
DC bus	
Voltage	48 V
Load	
Minimum power	50 W
Maximum power	1000 W

Numerical simulation

To test the effectiveness of the proposed power management strategy applied to hybrid energy system (Fig. 8.). The simulation under Matlab/Simulink over a period of two different days has been performed.

The different parameters of each subsystem used are listed in Table 4.

In order to verify the performance of the system in the different situations, simulation studies have been carried out,

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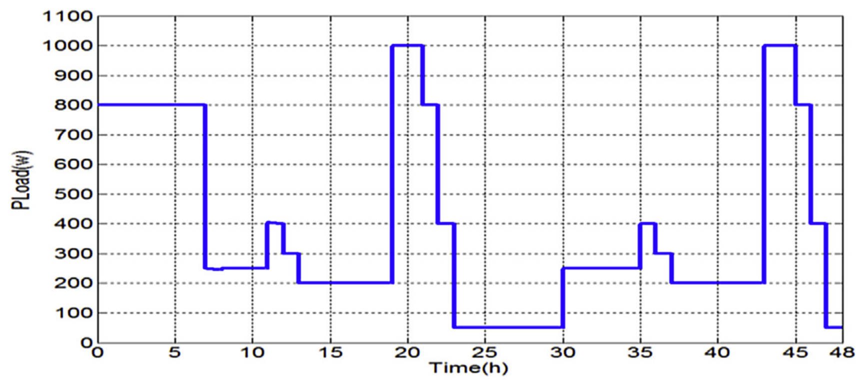

Fig. 9 – Profile of the load power.

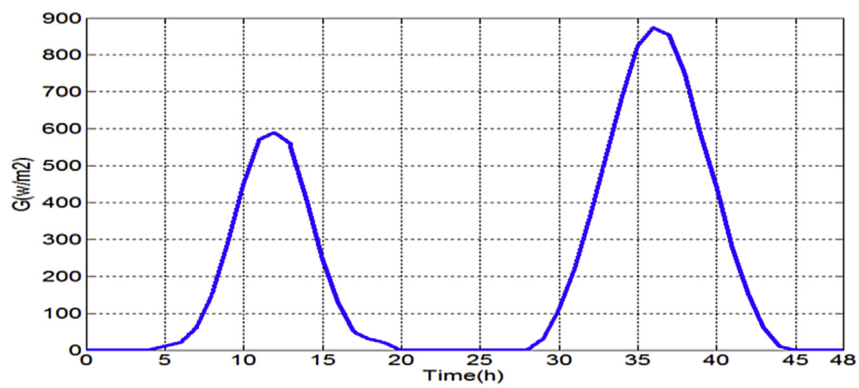

Fig. 10 – Profile of the solar irradiation.

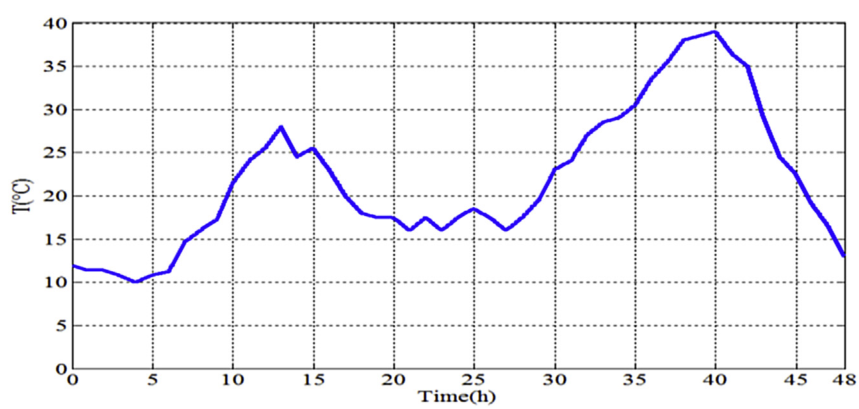

Fig. 11 – Profile of temperature.

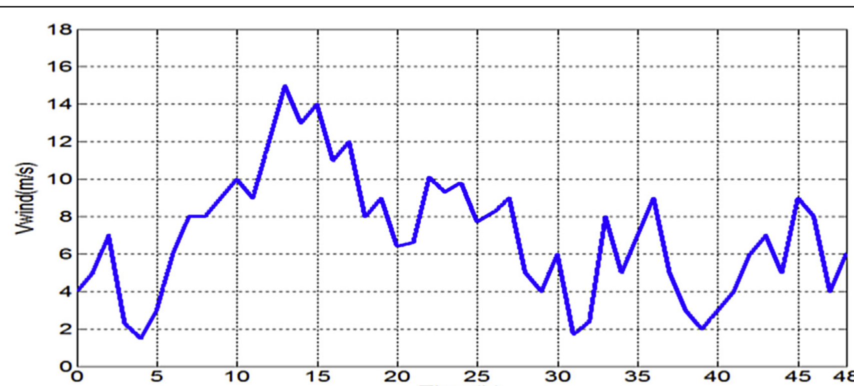

Fig. 12 – Profile of the wind speed.

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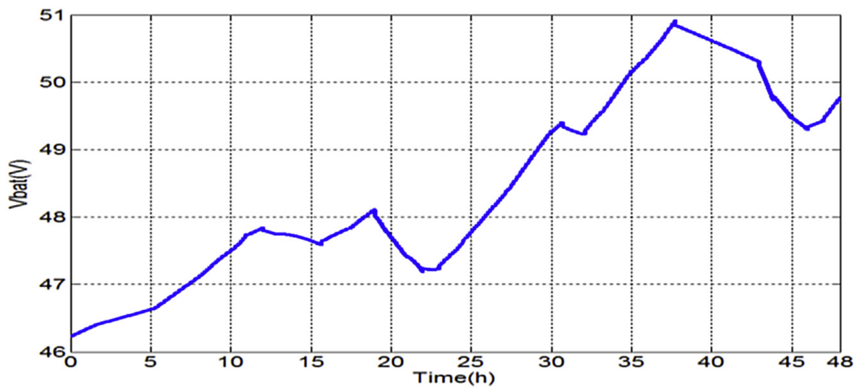

Fig. 13 – Shape of the battery voltage.

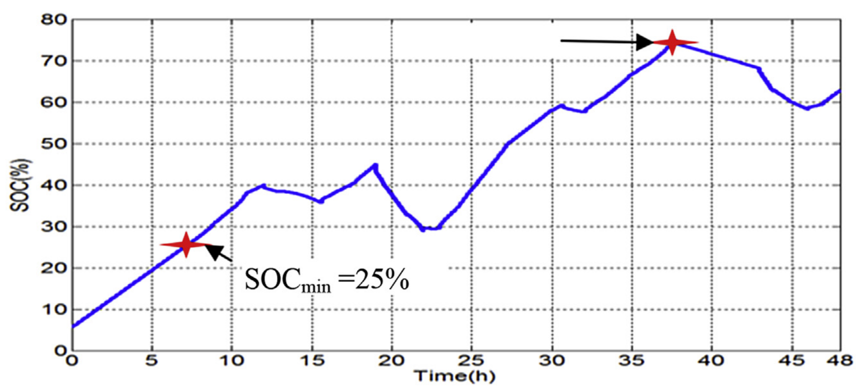

Fig. 14 – State of charge of the battery.

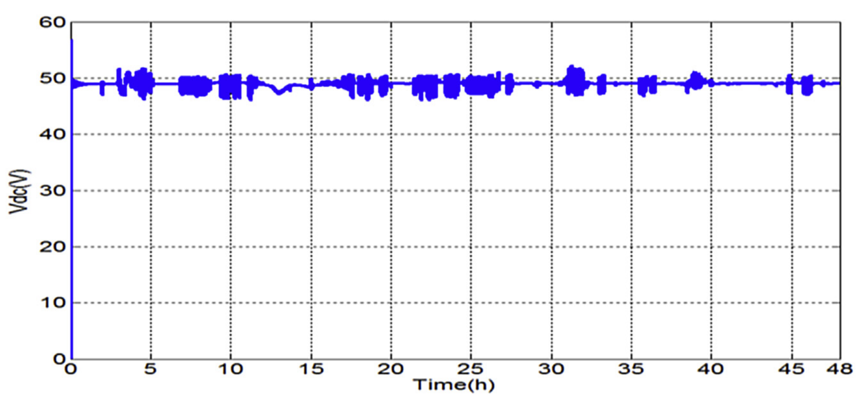

Fig. 15 – DC voltage.

and to test the robustness of the proposed method the profiles are chosen: the power of the load (Fig. 9), solar irradiance (Fig. 10), temperature (Fig. 11) and wind speed (Fig. 12) for two different days.

Figs. 13 and 14 show respectively the shape of the battery voltage and the state of charge of the batteries, noting that they have the same shape. It can be seen in Fig. 14 that the state of charge of the batteries SOC lowers than the SOC_{min} which is limited to 25%. This is justified by the initial conditions chosen, namely the initially discharged batteries, the zero irradiation and the low wind speed, in order to show or present all the modes of operation described in the screen.

The DC voltage is kept constant (Fig. 15). Fig. 16 shows the different powers supplied by the several used sources (PV, wind turbine, Diesel generators and batteries.

From these results, it can be said that the objective of the Fuzzy Logic Controller-based energy management method of the proposed hybrid system is achieved.

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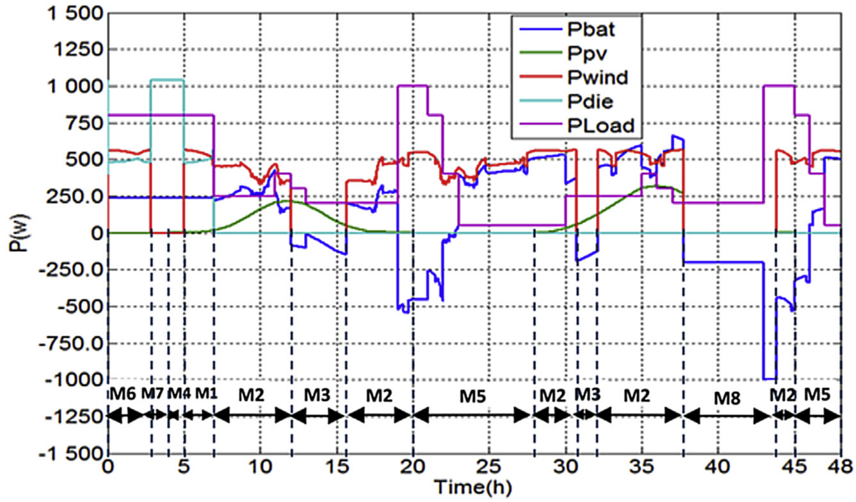

Fig. 16 – **Power waveforms during the two different days.**

Conclusion

In this paper, energy management based on Fuzzy Logic Controller of hybrid system Wind/Photovoltaic/Diesel with storage battery has been presented. The numerical simulation results show good performances and the load demand is at any time satisfied by the different sources which enables us to conclude that this combination of variant sources with energy management control (PMC) based on fuzzy logic control permits to get electrical production continuity. The developed EMC reaches the assigned objectives where the simulation results clearly show the good operation of the hybrid system whatever the different weather conditions. It would be interesting to implement the model for several areas such as electrification, pumping of water.

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