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Research paper

Energy management for renewable electricity production system including hybrid hydrogen sub-system

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ABSTRACT

An optimal energy management technique for hybrid power generation with a hydrogen storage system is presented in this study; based on a fuzzy controller (FC) and local controls for each converter. The system includes mainly a photovoltaic generator (PVG), a fuel cell, a hydrogen storage tank, an electrolyzer, batteries, and electrical converters. Energy management aims to manage the excess energy produced by the PVG to meet load demand taking into consideration the system's cost and lifespan. The MATLAB-Simulink environment is used to simulate the proposed energy management technique; the obtained results show considerable limitation in current/voltage constraints, which prolongs the hydrogen subsystem's lifespan and reduces the system's cost.

1. INTRODUCTION

The intermittency of solar energy requires further study to meet the energy needs of consumers. Although solar photovoltaic is a clean energy resource, its power output is dependent on meteorological conditions, making the production estimate inaccurate. Storing excess energy and using it at times of shortages makes solar systems a more competitive energy source. Conventional battery storage remains expensive, but hydrogen energy storage systems have proved to be promising and competitive for the future (Magrini et al., 2017; Ivalin, et al., 2020). In all hybrid systems, it is necessary to have suitable energy management to satisfy the load's energy requirement when the photovoltaic generator is incapable of supplying energy for a specific period of the day.

References (Lux B, Pfluger B, 2020; Dash et al., 2015; Higuita et al., 2017) have shown some examples of energy management, the objective is to test the hydrogen hybrid system's performances at all times and for long periods, e.g. months, years or even during the lifetime of the hybrid system. However, the

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component costs were not taken into account in the proposed management system. An economic variable has been developed to calculate the system's total cost in the management method developed (Sadigh et al., 2015). In this paper, the energy sources' costs have been calculated and considered, and a fuzzy controller has been used to optimize some parameters used in the management system. Costs are annually updated based on the lifespan of each component. The study is carried out over one year and estimates the number of fuel cells, electrolyzes, and batteries required for a 20-year lifetime of the studied system.

2. STANDALONE HYBRID SYSTEM

The studied system configuration is presented in Fig 1. The hybrid system comprises a PVG, an electrolyzer, a fuel cell, and hydrogen tanks interconnected to the DC bus. A battery provides the transient energy demand and peak loads required during peak consumption; the battery provides all other load variations.

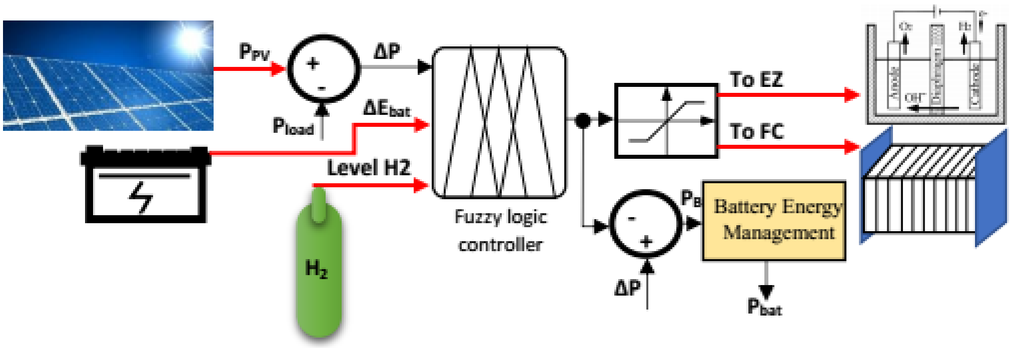


Fig1. Overall energy management system.

2.1 Solar photovoltaic arrays

PV generator is the principal energy source of the studied system. Production of electrical energy is based on photovoltaic arrays; which are made up of cells manufactured from semiconductor material. The electrical energy coming from the photovoltaic generator is given by Eq. 1 and Eq. 2 (Tabanjat et al., 2018; Lalouni. Belaid, 2021).

$$P_{PV} = i_{PV}.V_{PV}.\eta_{PV} \tag{1}$$

$$i_{PV} = i_L - i_0\left[\exp\left(\frac{q(V_{PV}+R_S i_{PV})}{AKT}\right)-1\right]-\frac{V_{PV}+i_{PV}R_S}{R_{Sh}} \tag{2}$$

2.2 Fuel Cell Dynamic Model

There are currently different types of fuel cells and a great deal of research has been carried out on the equivalent electrical model depicted in Fig. 2. A single cell's voltage can be calculated using the following equation (Zerhouni et al., 2015; Uzunoglu et al., 2009; Khan et al., 2005).

$$V_{FC} = E_{Nernst} - V_d - V_{ohm} \tag{3}$$

$$E_{Nerst} = 1.229 - 0.85.10^{-3}(T - 298.15) + 4.31.10^{-5}T\left[ln(pH2) + \frac{1}{2}ln(pO2)\right] \quad (4)$$

$$\frac{dV_d}{dt} = \frac{1}{C}i_{FC} - \frac{1}{\tau}V_d \quad (5)$$

$$V_{ohm} = i_{FC}\left(R_M + R_C\right) \quad (6)$$

Equation 7 can be used to calculate the hydrogen consumption of fuel cells (M_{FC}).

$$M_{FC} = 3600.\frac{i_{FC}.m_{H2,act}}{2.F.m_{H2,th}} \quad (7)$$

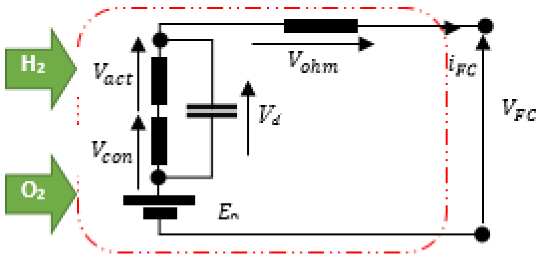


Fig 2. Simplified circuit of the Fuel Cell.

2.3 Electrolyzer

The electrolyzer's hydrogen production rate can be calculated using Faraday's law. The productivity of the electrolyzer, n_{H2} (mol/s), is given by the following formula (Xueqin et al., 2020; Kadri, et al., 2020).

$$n_{H_2} = \frac{n_F.n_c.i_e}{2.F} \quad (8)$$

2.4 Battery

The battery is a storage device designed to store electrical energy from the photovoltaic resource. It is used as an additional power source to improve the PEM fuel cell's flexibility and lifetime. Equation 9 gives the battery's energy storage capacity (Wang et al. 2020; Liu, et al., 2021).

$$E_b = \int\left(P_{b.discharg} - P_{b.charg}.n_b\right).dt \quad (9)$$

The batteries' state of charge SOC can be calculated, using the battery's current (i_{bat}) and capacity (Q), as follows (Liu, et al., 2021).

$$SOC(\%) = 100\left(1 - \frac{\int i_{bat}.dt}{Q}\right) \quad (10)$$

2.5 Hydrogen tank

The Electrolyser produces hydrogen and stores it in liquid or gaseous form in storage tanks. The tank pressure is calculated by the following equation (Ahmed et al., 2021; Bhat Nempu, et al., 2008; Gerlach et al.2021; Zidane et al. 2022).

$$P_{tank} - P_{tank,init} = z\frac{N_{H_2}.R.T_{tank}}{M_{H_2}.V_{tank}} \tag{11}$$

3. MANAGEMENT STRATEGY APPLIED

The energy management system is tasked with the energy flow monitoring between the PVG, batteries, electrolyzer, fuel cell, and load consumption. It's designed to meet charging needs throughout the day and after sunset. In this work, the fuzzy controller delivers the current references of the hydrogen subsystem, these references are injected into the local controls of the DC/DC converters, and local control to ensure the regulation of the fuel cells and the electrolyzer current has been adopted. Figure 3 shows the fuzzy controller's structure. It is designed to prevent the FC/electrolyzer from starting and stopping and to enhance their respective lifetimes while taking the current constraint into account.

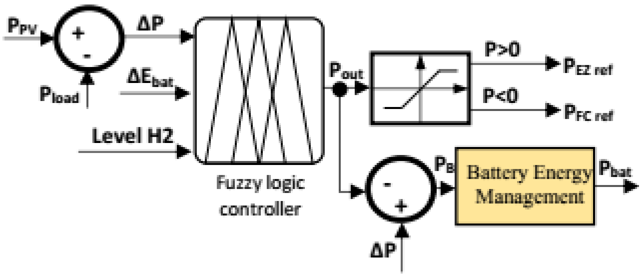


Fig 3. Fuzzy logic supervisor and controlled system.

The battery is used as a backup source to absorb and compensate for the energy in the DC bus. Then it undergoes a significant number of charge/discharge cycles and preserves its lifetime by limiting its discharge to Soc_{min}=40% while maximizing the charge to Soc_{max}=100%. The battery energy management complementary is depicted in Fig 4.

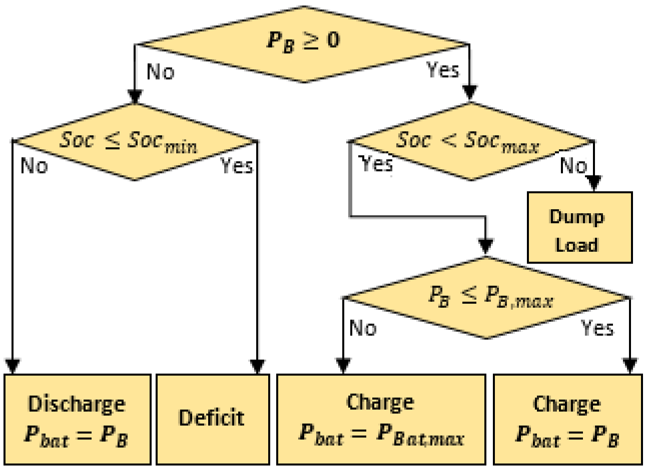
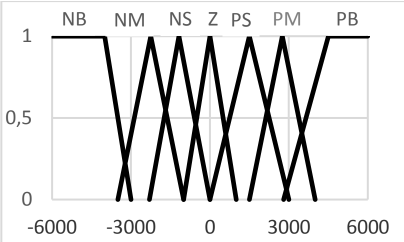
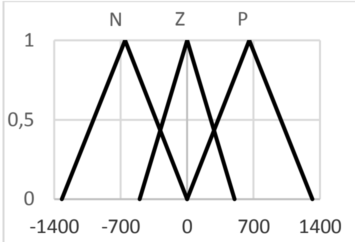


Fig 4. Flowchart of the battery energy management algorithm.

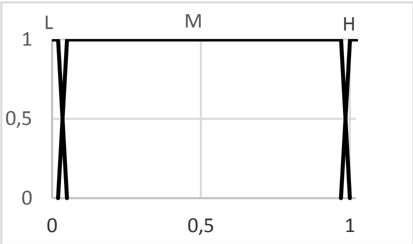
The fuzzy controller's variables are ΔE, ΔE_{bat}, and Level H2, represented respectively by seven linguistic variables and three linguistic variables for ΔE_{bat} and Level H2. The output, Pout is represented by five linguistic variables as presented in Fig 5 (Zidane et al. 2022). Table 1 shows the basis of the control rules, which will concretize the defined evaluation criteria.



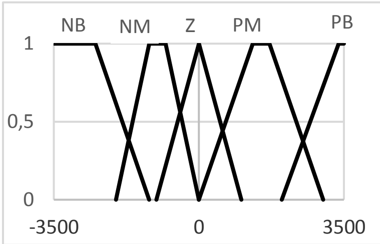
(a) ΔE input



(b) ΔE_{bat} input



(c) Level H2 input



(d) P_{out} Output

Fig 5. Fuzzy controller inputs and output.

TABLE 1. FUZZY CONTROLLER RULE BASE

ΔE		NB	NM	NS	Z	PS	PM	PB
ΔE_{Bat}	**L_H2**							
N	**L**	Z	Z	Z	Z	Z	PM	PB
	M	NB	NB	NB	Z	Z	Z	PB
	H	NB	NB	NB	Z	Z		
Z	**L**	Z	Z	Z	Z	PM	PM	PB
	M	NB	NB	NM	Z	Z	PM	PB
	H	NB	NB	NM	Z	Z	Z	Z
P	**L**	Z	Z	Z	Z	PM	PB	PB
	M	Z	Z	Z	Z	PM	PB	PB
	H	Z	Z	Z	Z	Z	Z	Z

4. SIMULATION RESULTS AND DISCUSSIONS

The proposed method was carried out and simulated under the MATLAB-Simulink environment, both structure and hybrid system sizing were the subject of previous work (Zidane et al., 2017). The fuzzy supervisory system provides power reference used to calculate the reference currents required in battery, EZ, and Fuel cell controllers. The PEMFC and EZ unit lifetime is shown in Fig. 6, as a function of the HS lifetime. When the FC reaches a nominal voltage 18% lower than the nominal start-up voltage, the element is replaced. The hydrogen tank storage level over the seasons is shown in Fig.7. The hydrogen tank may be completely discharged, since the hydrogen level and the cycle numbers do not affect the tank's lifespan. The demand is easily met; during spring and summer, more than 40% of the hydrogen is stored. However, there are some days in the autumn and winter when the reservoir is emptied.

Figure 8 shows the power evolution over the seasons (battery power, fuel cells' generated power, and supplied to the EZ and Delta P corresponds to the difference between the generated and the requested power. To better visualize the evolution of the Hybrid system power during the four seasons presented in Fig. 8 and in Fig .9 that represents their zooms. It can be seen that the battery acts like an energy damper during generation peaks, reducing the current peaks expected to be supplied to EZ. The battery also compensates for the energy during peak demand, which shares with the PEMFC, the major charging power part.

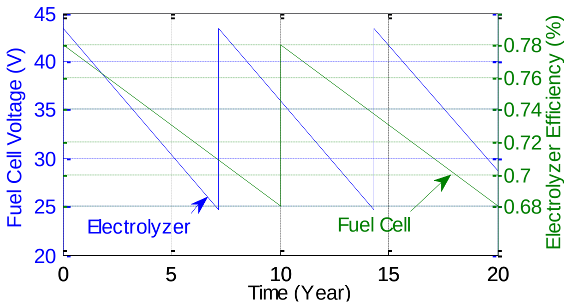


Fig 6. Unit life of the PEMFC and EZ.

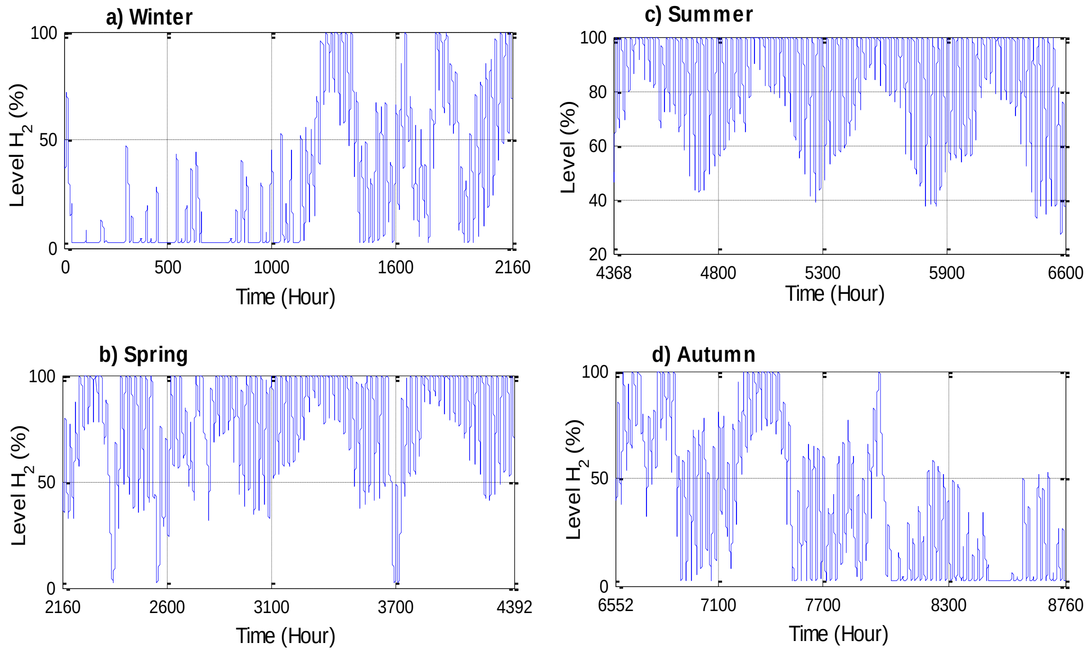


Fig 7. Hydrogen tanks' storage level.

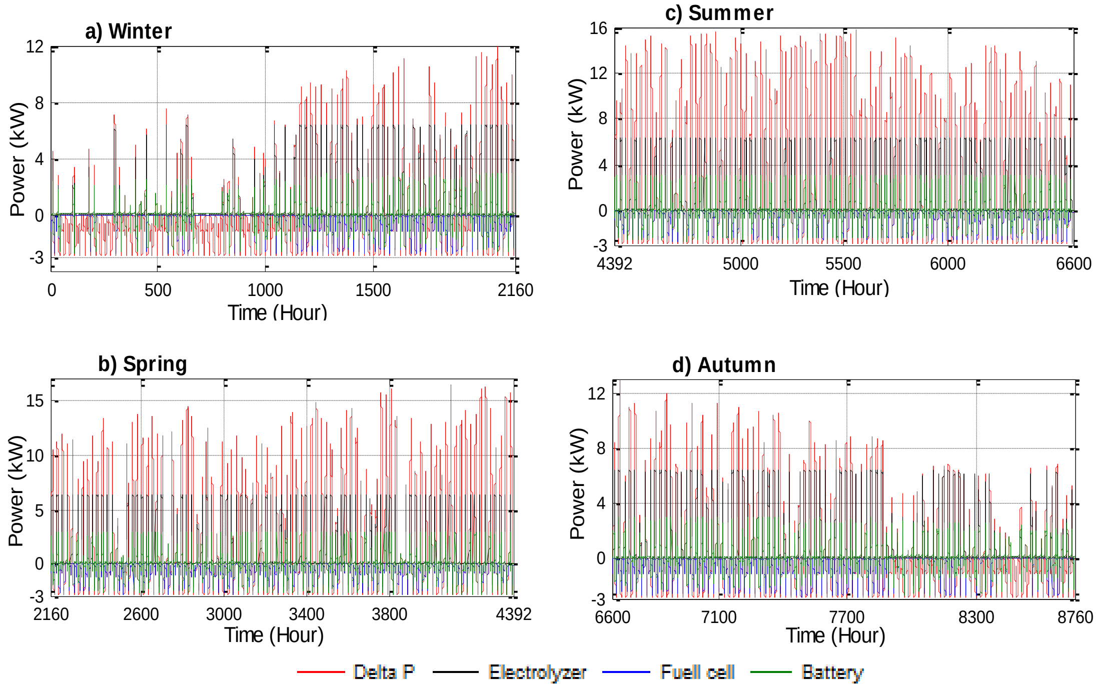


Fig 8. Power evolutions over the seasons.

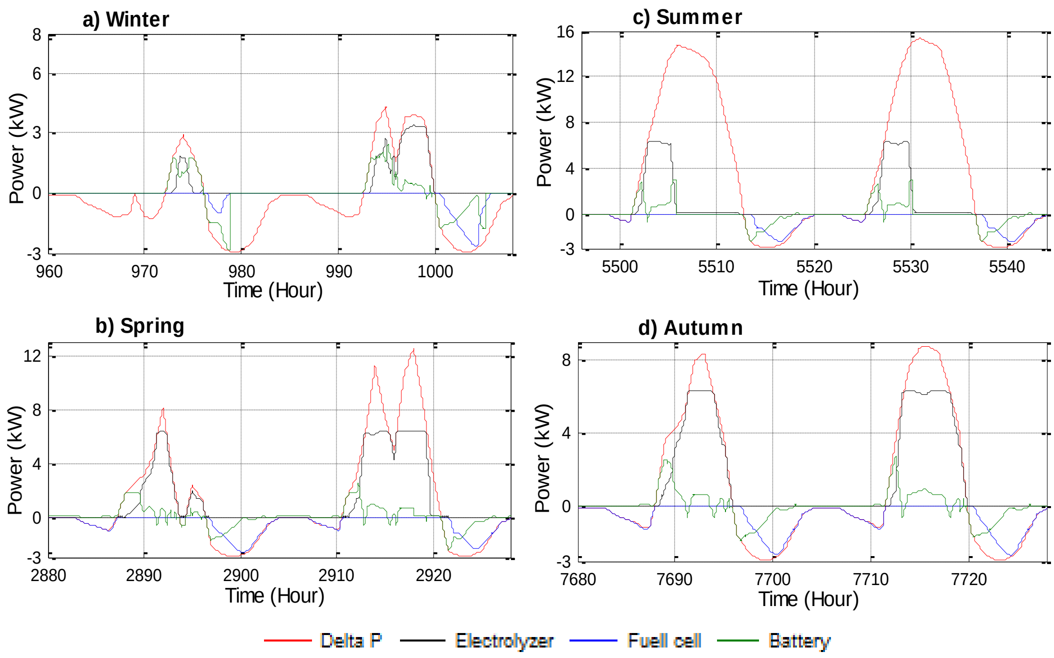


Fig 9. Zooms of the Hybrid system’s power evolution during two days (over the seasons).

5. CONCLUSION

An advanced energy management method for a Hybrid system including a PV generator, batteries, and hydrogen subsystem has been investigated in this paper. The aim was to perform an operational test of the fuzzy management method in real time based on the maximum current/voltage of the PEMFC and the electrolyzer. A significant improvement in current peaks is shown in the simulation results compared to conventional management. The use of a battery as an energy buffer makes fuzzy logic management more important in controlling the PEM and EZ currents, thus avoiding operation at maximum power at times of consumption or production peaks. Finally, the proposed method has made it possible to manage instantaneous energy as a function of the generated energy, consumption, and lifetime of the most costly elements, thereby extending the overall system's lifetime.

NOMENCLATURE

V_{PV}	PV voltage[V]	pO_2,	Partial pressure of oxygen
i_{pv}	PV current [A]	pH_2	Pressure of hydrogen
R_{Sh}, R_S	Shunt, series cell resistances (Ω)	η_{pv}	PV array Efficiency
A	Ideality factor	i_{FC}	Fuel cell current (A)
q	Electron charge	R_M	Membrane resistance (Ω)
K	Boltzmann constant	Rc	Contact resistance (Ω)
T	Cell temperature	$m_{H2,th}$	Theoretical hydrogen flow rates through FC
E_{Nernst}	FC cell Thermodynamic potential	$m_{H2,act}$	Actual hydrogen flow rates through FC
V_{ohm}	Ohmic voltage drop	n_c	Number of cells in series
$P_{b.disharg}$	Battery discharging power	F	Faraday constant
$P_{b.harg}$	Battery charging power	n_F	Faraday efficiency

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