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A Novel Supervisory Command Integration for Large-Scale of a Solar Energy/Fuel Cell/Ultra-capacitor

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Abstract: In this paper, we present a Stand-alone Power system (SPS). The goal of this system is the ensuring of the electricity production without interruption in remote areas. It consists generally of a five components which are a solar energy, an energy storage that combines a water electrolyze and a storage gas tank, an energy conversion based on a proton exchange membrane fuel cell (PEMFC), an ultra-capacitor storage (UCap) and a suitable energy management unit to manage and to supervise the system operation of the hybrid system. This combination can ensure the optimal behavior of the load with the respect of the slow dynamics of the PEMFC. The integration UCap ensures the elimination of the slow dynamics of the PEMFC during the transient event. A Novel supervisory command is proposed. The modeling of the overall system is given and the obtained results are presented and discussed.

Keywords: Solar Energy, Proton Exchange Membrane Fuel cell, Ultra-capacitor, Supervisory Command, Energy Management.

1. Introduction

The renewable energy sources (solar, wind, geothermal, etc.) attract more attention as an alternative energy. Among the stand-alone renewable energy sources, the photovoltaic energy has been widely utilized in low power applications. It is also the most promising candidate for research and development for large scale users as the fabrication of low cost PV devices becomes a reality [1]. In fact, Hydrogen may play an important role as an energy carrier of the future and may be converted into useful forms of energy more efficiently than fossil fuels [2]. So, it can be used in industry, residences, transportation, and mobile applications. In addition, the development of efficient, compact and reliable energy storage system based on hydrogen technology represents a challenge for seasonal storage based on renewable hydrogen that could be used in stand-alone systems [3]. Considering that hydrogen production from water electrolysis can be performed using renewable energy, PEM fuel cells emerge as one of the most clean and promising alternatives to reduce fossil fuel dependency [4].

In comparison to commonly used battery storage, electrolytic hydrogen (H_2) is well suited for seasonal storage applications because its inherent high mass energy density leakage from the storage tank is insignificant and it is easy to be installed anywhere [5]. In addition, the fuel cell generator, especially the PEMFC, is a good option to integrate with the SEC power since it is characterized with many good features such as high efficiency, fast response, modular production and fuel flexibility [6]. The combination of Fuel cell component with the ultra capacitor component is an attractive choice due to their high efficiency, fast load-response, flexible and modular structure for use with other alternative sources such as PV systems or wind turbines [7]. A lot of research and development work have been carried out on hybrid electric system and strategies of system management for decades together and quite a good number of publications are available in literature. Also recently a considerable research work is

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carried in areas related to solar hydrogen systems and quite a number of papers are available in literature.

Kh et al. [8] studied a stand-alone system under which combined of a solar photovoltaic and PEM fuel cell based Integrated energy system, which consist of a photovoltaic generator, a proton exchange membrane (PEM), Battery, fuel cell and Power Conditioning unit. Li et al. [9] studied three stand-alone photovoltaic power systems using different energy storage technologies and modeled photovoltaic modules, fuel cells, electrolyzes, compressors, hydrogen tanks and batteries. Uzunoglu et al. [10] focused on the integration of photovoltaic fuel cell and ultra-capacitor systems for sustained power generation. Phatiphat T et al. [11] presented an original control algorithm for a hybrid energy system with a renewable energy source integrating a polymer electrolyte membrane fuel cell (PEMFC) and a photovoltaic (PV) array with a supercapacitor (ultra capacitor) module. The main of the proposed control strategy is the ensuring of the load requirements even at the system fluctuations. Djamila R et al. [12] present the different hybrid systems with fuel cell. Then, they give a system study with a hybrid fuel cell photovoltaic generator whose role is the production of electricity without interruption in remote areas. For this reason, they present a suitable power conditioning units (PCU) to manage the system operation of the hybrid system.

Our work is specified by studying and developing a Novel Supervisory Command (NSC). Compared to other methods, we can classify our approach as a promising method of the system monitoring. Indeed, it replaces the use of battery by the UCap component in one hand. In other hand, we present a new supervisor method and solve two important problems. The first problem is relative to the slow dynamic of the PEMFC and the second one is concerning the energy storage device (UCap) which can restore the braking energy and is a large capacitance device, is more efficient than the battery due to the limitation on a life cycle, the prompt storage and stored energy consumption.

The system under study is simulated by using load consumption profile.

The paper is organized as follows. Description and methodology of the SPS are given in Section 2. Section 3 discusses the energy management of the SPS. Section 4 presents the control strategies developed for the energy management system of the SPS. The simulation results are discussed in Section 5, and finally, Section 6 establishes the conclusions.

2. System description and methodology

A. *Design of the global system*

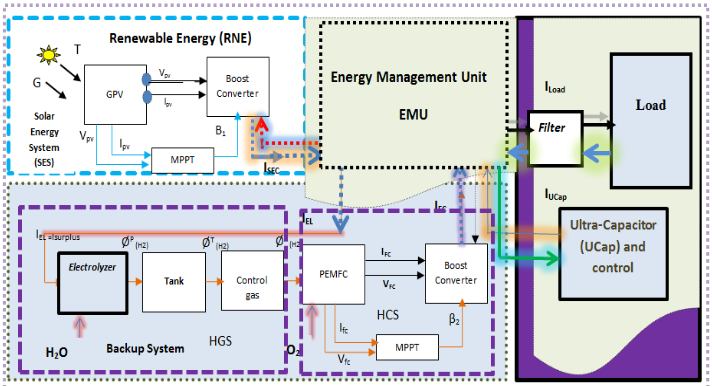

Figure 1. Design of the global System

B. Solar Hydrogen generation system

In this section, The SES system is taken as the primary source. Moreover, a Hydrogen Generation System (HGS) composed of a PEMEL and Hydrogen Tank Storage (HTS) is considered to store in hydrogen form the. Our disgn studied system configuration is presented in figure 1.

B.1 Solar energy system

A photovoltaic module is formed by connecting many solar cells in series and parallel. Considering only a single solar cell; it can be modeled by utilizing a current source, a diode and two resistors. This model is known as a single diode model of solar cell. So, the characteristic equation for a photovoltaic cell is given by [13]:

$$I_{PES} = N_p I_{ph} - N_p I_s \left[exp\left(\frac{V_{SES}}{N_s V_q} + \frac{I_{SES} R_{sc}}{NpV_q} \right) - 1 \right] - \frac{N_p}{R_{sh}} \left(\frac{V_{SES}}{N_s} + \frac{I_{SES} R_{sc}}{N_p} \right) \quad (1)$$

While the photocurrent I_{ph} can be expressed as:

$$I_{ph} = \left[I_{cc} + T_j \left(T - T_{STC} \right) \frac{G}{G_{STC}} \right] \quad (2)$$

B.2 Hydrogen generation system

The Hydrogen generation system (Called HGS) is mainly composed of a Water Electrolyze and Compressor/Tank Storage systems. Considered as a promising technology, the Electrolyze consists of a stack of electrochemical cells in series. Each cell is the site of an electrochemical reaction[14]. The generated H_2 flows out at the cathode and the generated O_2 and residual H2O flow out of the anode. The current-voltage characteristic I_{EL}-V_{EL} is given by:

$$Vel = Erev + Vact + Vcon + Vohm \quad (3)$$

Given Erev is a reversible voltage, Vact an activation overvoltage, Vcon a concentration voltage and Vohm an Ohmic voltage. After hydrogen has been produced, hydrogen flow rate gas has to be stored in Tank storage system. The pressure in the hydrogen tank can be derived from the Van der Waals equation of state for real gases as [15].

B.3 Hydrogen consumption system

The Second Energy System (SES) which is directly connected to the DC-DC boost converter. The SES is composed by the PEMFC system which is directly connected to the DC-DC boost converter. In fact, PEMFC has long been known as a converter of hydrogen into energy (electrical + thermal), and it has a high efficiency which is proven by the comprehensive research carried out on this technology worldwide. The boost circuits produce the output voltage by charging an input inductor with current, from an input voltage source, and then discharge the inductor into an output capacitor. The chemical energy ($Ø^c$ (H_2), Air) is converted by the PEMFC in a middle temperature (20°-80°) [16]. The operation voltage (called V_{FC}) of a single cell can be calculated by combining the open circuit voltage with the effects of activation, the ohmic resistance and the concentration (equation 3).

$$V_{FC} = E_{Nernst} - v_a - v_{ohm} - v_{con} \quad (4)$$

The fuel requirement of the HCS system is related to the production of the PHGS system. In fact, the hydrogen generated quantity by the PHGS system can be defined as:

$$\phi^P(H_2) = \eta_{F_{el}} \frac{N_c}{2F} I_{Surplus} \quad (5)$$

While the hydrogen consumed quantity of the HCS system can be determined by the following equation:

$$\phi^C(H_2) = \frac{N_{fc}}{\eta_{F_{FC}} 2F} I_{SES} \quad (6)$$

B.4 Ultra-capacitor device

With several orders of capacitance values greater than that of ordinary electrolytic capacitors, UCap banks have much higher energy storing capability owing to the charge double layer effect. Compared to batteries, they can achieve much higher power densities but have lower energy densities [17]. The UCap banks are also considered as attaining virtually infinite charge/discharge cycles and they are well suited for short, strong transient loads. Unlike batteries which are inefficient and have short life cycles under such loading conditions, they possess relatively higher efficiency and longer life cycle. As in conventional capacitors, the energy stored by a UCap is directly proportional to the square of the voltage as :

$$E_{UCap} = \frac{1}{2}.C_{UCap}.U_{UCap} \qquad (7)$$

While the voltage state of UCap can be described as follows:

$$U_{UCap} = U_{in}..exp(\frac{-t}{R_{UCap}.C_{UCap}}) \qquad (8)$$

3. Energy management of the SPS

In this section, the supervisory algorithm for HES is (see Figure. 2). The proposed algorithm is the main area that ensures correct operation between the PES, the HCS and the load. The latter is based on the coefficients of the decision system which are ε_1 and ε_2. In the detected variables for this supervisory approach, we have the photovoltaic current (I_{PES}), the HCS current (I_{HCS}), the UCap current (I_{UCap}),, the Load current (I_{Load}), and the coefficients of activation (Δ_1, Δ_2 and Δ_3 respectively for the PES and the HCS).

A. First scenario

This scenario has as objective, the favorable choice of the electrical power source, ensuring the proper functioning of the load. Indeed the variables detected in this mode are the PES current IPES, the WEL current, the HCS current and the load current I_{Load}. This mode is associated with a number of conditions that can be cited as follows:

For ε_1=I_{PES}-I_{load}

If $\varepsilon 1>0$ then (Δ_1=$_1$), (Δ_3 =1) and (Δ_2=0) → (I_{HCS} =0) and (I_{HGS} = $I_{surplus}$)
and $\varepsilon 3 = Ø^P(H_2) - Ø^S_{max}(H_2)$ → $I_{surplus}$=$I_{Electrolyzer}$=0 and $I_{load\ -\ UCap} \neq 0$

If $\varepsilon_1<0$ then (Δ_1=0) and (Δ_3 =0) → ε_2=I_{HCS}-I_{load}

If $\varepsilon_2>0$ then (Δ_2=1) ➔ I_{PEMFC}=0 and $I_{disch\_UCap} \neq 0$

If $\varepsilon_2<0$ then (Δ_2=0) ➔ I_{PEMFC}=0 and $I_{disch\_UCap} \neq 0$

$I_{PEMFC} \neq 0$ et I_{disch_UCap}=0

B. Second scenario

This scenario is dedicated to the evolution of the H_2 quantity in the tank storage. Indeed, two main parameters are presented here which are the $Ø^P$ (H2) and $Ø^C$ (H_2).

B.1 The first assumption

For $Q^{ness(}H_2)=f(I_{Load})$

If $Q^{ness}(H_2)>Q^S_{max}$ and $Q^S(H_2) = Q^S_{max}$ → QC(H2)= Q^S_{max}- Q^S_{min} → I_{HCS}=I_{Load}

If $Q^{ness}(H_2)< Q^S_{max}$ → second assumption

B.2 The Second assumption

For $Q^{ness}(H_2) < Q^{Smin}$ → $Q^C(H_2)=Q^{ness}(H_2)$ → I_{HCS}=I_{Load}

For $Q^{ness}(H_2) > Q^S_{min}$

If $Q^S(H_2) > Q^S_{min} \rightarrow QC(H_2) = QS(H_2) - Q^S_{min} \rightarrow I_{HCS} = I_{Load}$
If $Q^S(H_2) < Q^S_{min} \rightarrow I_{HCS} = 0$

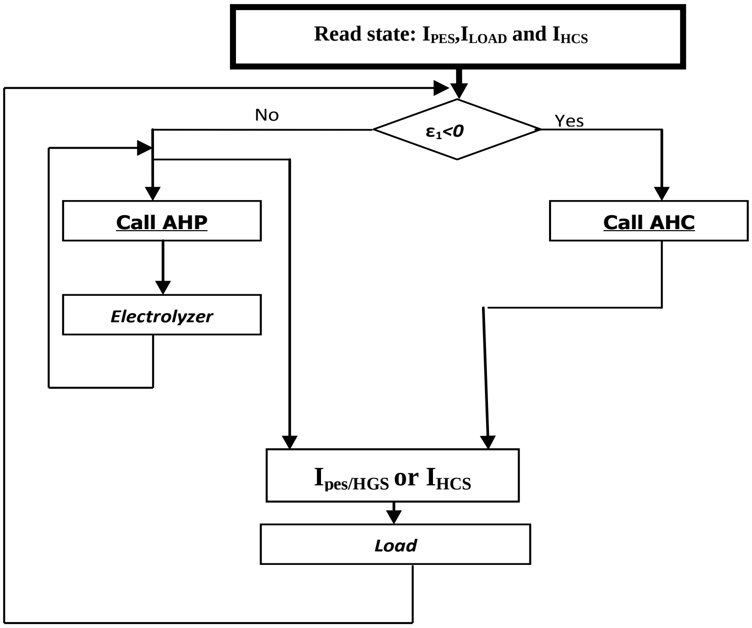

Figure 2. The supervisory control Algorithm

The algorithm to supervise the hydrogen production (AHP) is proposed to control and to manage the flow rates of H_2 gas. The AHP algorithm represents the complementary area that selects the necessary decision to activate the Electrolyze, to control the flow of H_2 gas delivered by the PEMEL and to maximize the quantity in the tank. All these decisions are based on the coefficient decision ε3. The Hydrogen consumption (AHC) is intended to control and to manage the flow rates of H2 gas consumed by the PEMFC and stored in the hydrogen tank. The AHC algorithm defines the procedure followed in order to select the necessary decisions regarding the activation/deactivation of the PEMFC, the discharge of the Ucap, the control of the H_2 gas flow consumed by the PEMFC and the minimum amount in the tank. These decisions depend on the coefficient decision ε2.The flowcharts of this algorithms are given by the following figures:

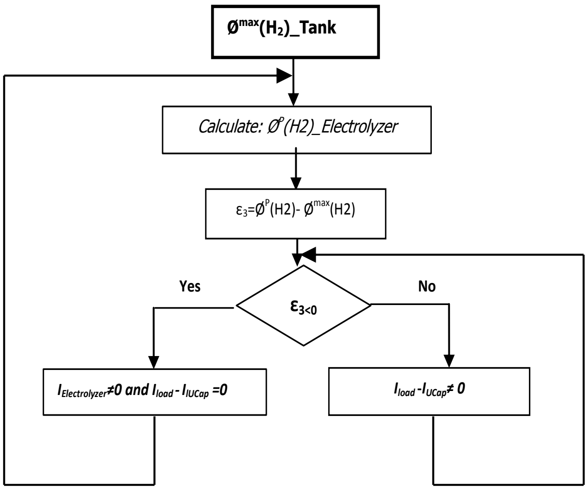

Figure 3. The Flowchart of the AHP algorithm

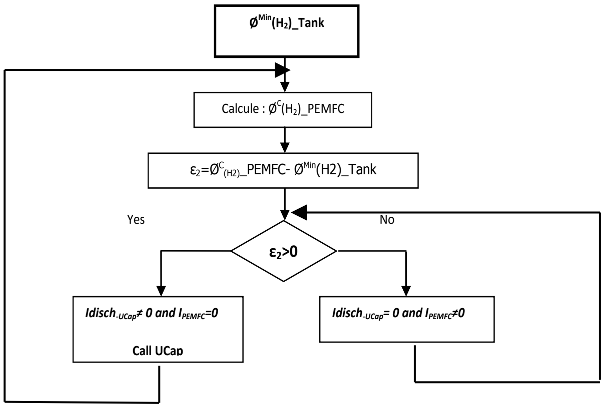

Figure 4. The Flowchart of the ACH algorithm

4. Simulation results discussion

In the simulation process, the aim is to observe the proposed system's behavior over a long period of time including the solar climatic conditions. The load profile, has been used to test the performance of the proposed SPS. The main objective for the applied Supervisory Algorithm Approach (SAA) in the integrated system is the satisfaction of the load requirement. RNE produce power that is basically used to meet the 1 kW constant load. The surplus of energy (Isurplus) can be potentially stored in the form of hydrogen and Oxygen ($Ø^s(O2)$) across water electrolysis and any shortage of electricity can be met by the Backup-device(PEMFC) provided that sufficient inventory of hydrogen is available. The operating strategy would have been quite simple if the solar energy power was constant or varying slowly over time. However, the large variability of power generation, mainly due to the aleatory behavior of the solar energy, increases the complexity of the management of the system [18]. So, Our developed algorithm includes two operating modes.

Mode A. Evaluation of the SPS when the I_{PES}-I_{load}>0

This mode is focus on the evaluation and the discussion of the SPS when $I_{PES}>I_{load}$ (Figure 5 and Figure 6). The behavior of the current inputs is presented by circles (a)in Figure.5. Also this mode is characterized by the activation of solar system (SPS). In fact, the activation this later will be sufficiently high to supply the load and the PEMEL (Figure.5). Before the start of this mode, our supervisory algorithm will test the minimum of energy within the UCap. This step is necessary, because it represents an rescue element that will produce the energy deficit for the load at maximum 20A. The electrical power load mode is described as below:

From 0 ~5 hours, the ISPS> ILoad

- The Solar energy system supply correctly the load
- $I_{surplus}=I_{Electrolyze}$ and Iload - UCap≠0, the Electrolyze produce the hydrogen gas($Ø^P(H_2)$)
- The excess energy is stored as hydrogen.
- we can remark that during this period the amount of H_2 exceeds the maximum level in the tank ($Ø^P(H_2)> Ø^{Max}(H_2)$), then the PEMEL will be disabled immediately and the excess energy will be stored in the Ucap (figure 6).

Mode B. Evaluation of the SPS when the I_{PES}-I_{load}<0

This mode is focus on the evaluation and the discussion of the SPS when $I_{PES}>I_{load}$

From 5~12.5 Hours, the I_{SPS}> I_{Load}.

In this mode the power must be obtained from the Backup system (PEMFC). This later, verifies that the power from the Solar system will be insufficient to operate the load (Figure.5). In this case, the PEMFC will be immediately activated to take over.

Indeed, the deficit of power can be obtained from the auxiliary generator circuit (PEMFC). In other words, the load is supplied by the HCS system. This later reacts by turning gas stored in the tank storage to operate the SPS. In fact, the Ucap is activated in parallel with the HCS to provide the energy deficit for the load. The tank storage will store and will provide the H_2 gas. In fact, when the Q^P(H2) becomes upper to Q^S_{max} the hydrogen generation has to be stopped. While, the tank storage disabled to provide hydrogen to the PEMFC when $Q^C(H_2) > Q^S_{min}$.

Mode C. Evaluation of the the behavior of PEMFC/Ucap

The PEMFC, the UCap and the load referential currents are visualized, in figure 6 in order to show the fact of the controller operation. With our adopted control strategy, the UCap supplies the instantaneous transient current, while the PEMFC current has a smooth response to the disturbance keeping a healthy PEMFC operation.

The figure 5 presents the SPS efficiency. It is extremely clear that the global efficiency is varied during the time. Hence, the SPS efficiency reaches at maximum 77 %.

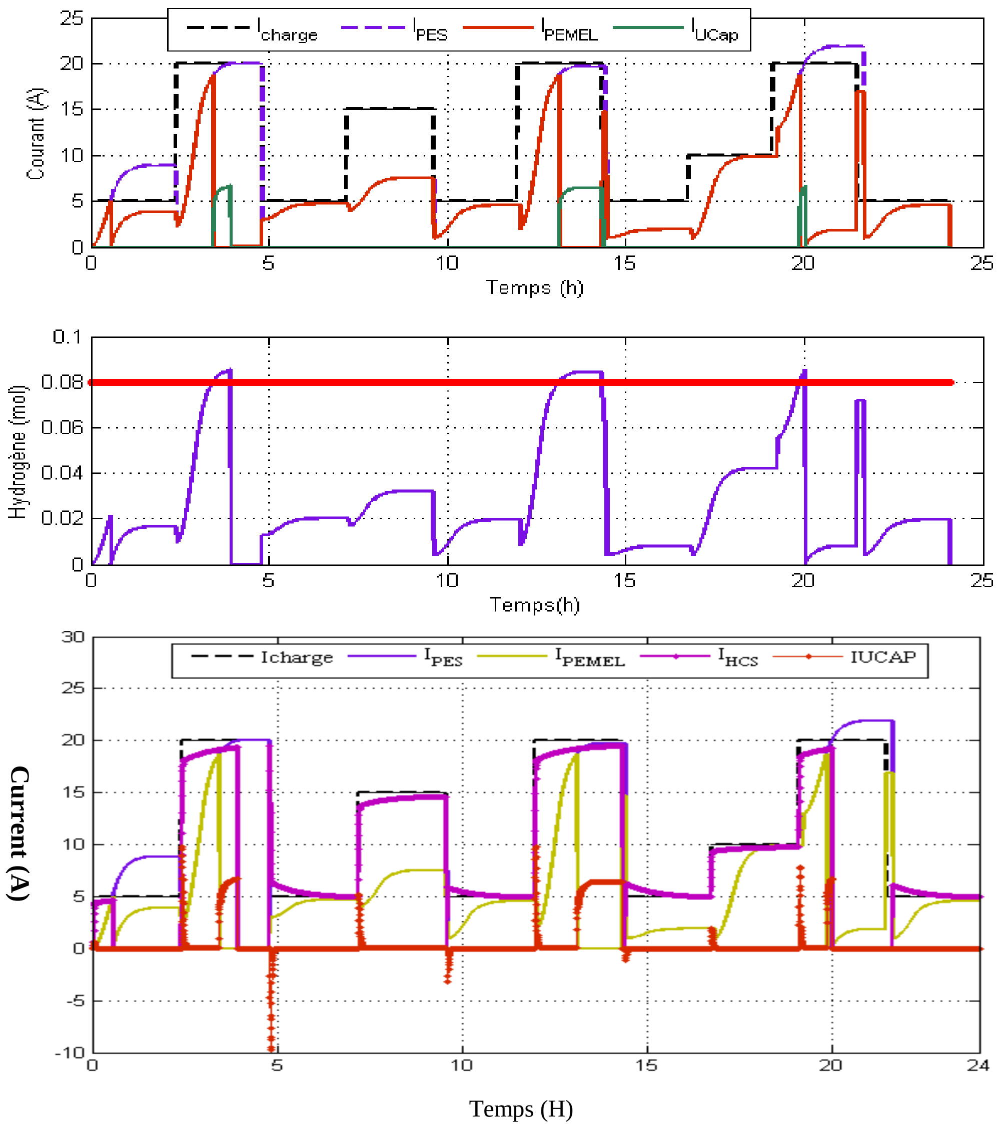

Figure 5. Variations of the SPS currents

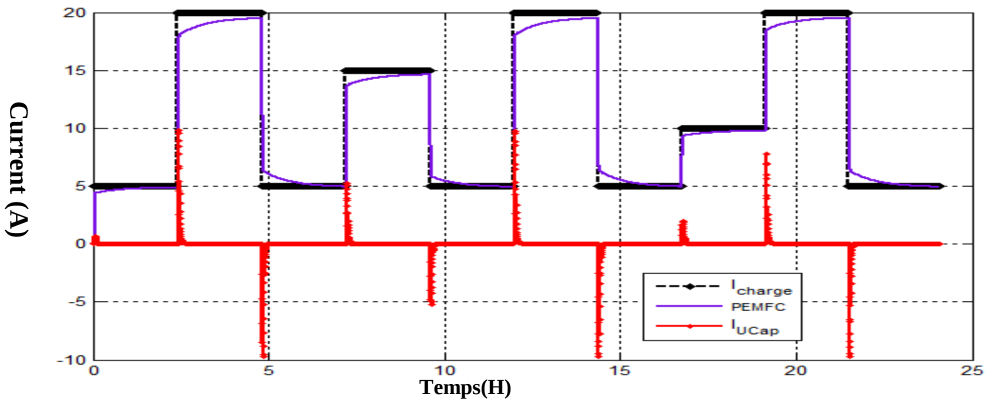

Figure 6. Variations of the PEMFC/Ucap currents

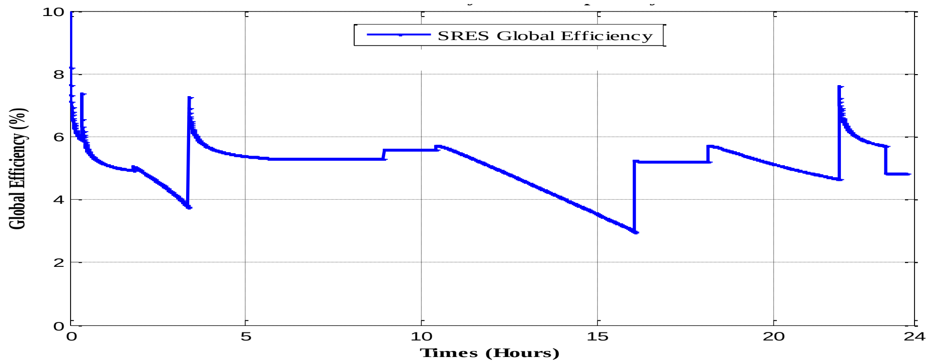

Figure 7. SPS Global Efficiency

Compared to the major related works [8] [9] [11], we can distinguish that our approch is able to allow the changement from one operation scenario to another according to the undergoing conditions and assumptions. For that, we can classify our approach as a promising method of the system monitoring. Indeed, our approach replaces the use of battery by the ultra capacitor component. Furthermore, the PEMFC in conjunction with Ultra-Capacitor can create a higher power with a fast dynamic response, which makes it well suitable for the load (see figure.5 and Figure.6). From our results, we have proved that our strategy has ensured the following assumptions:

a. Respect of the slow dynamics of the PEMFC and the guarantee of the transient load using the UCap.
b. Assure the load requirements for any fluctuations
c. Ensure that the ultra-capacitor keeps the optimal power.
d. For example, from the results in Figure. 5, we have found that from 1 to 12.5 Hours, the UCap current behavior increases ($I_{load} > I_{PEMFC}$) and from 15 to 24 hours the UCap current behavior decreases. These results prove the reliability and the efficiency of our approch.

5. Conclusion

In this paper, a Stand-alone renewable energy system (SPS), including PES, HGS, HCS and SCap subsystems, is investigated. In fact, a new approach of energy management is evaluated to supervise and range the distribution of power in the system. Thus, the proposed algorithm, which is based on two scenarios, keeps sustaining the load in spite of the weather conditions as well as the transient events. The applied strategy respects the slow dynamic of the PEMFC and the guarantee of the transient load using the UCap.

Our future work includes the adaptation of new control systems, optimization techniques and energy management units. This work will be done using different methods in order to prove the electrical energy economy.

NOMENCLATURE

G	: Solar radiation (W/m2)	I_{PES}	: Photovoltaic output current (A)
V_{PES}	: Photovoltaic output voltage (V)	T	: Photovoltaic temperature (°C)
Np	: Number of photovoltaic parallels cells	Iph	: Photocurrent (A)
Ns	: Number of photovoltaic series cells	Vq	: photovoltaic thermal voltage (V)
Is	: Photovoltaic saturation current (A)	Ta	: Ambient temperature (°C)
Rsc	: Series resistance (Ω)	η_{EL}	: Electrolyze efficiency
Rsh	: Shunt resistance (Ω)	V_{FC}	: PEMFC output voltage (V)
Pmax	: Maximum output solar power (W)	N_{FC}	: Output PEMFC voltage (V)
A	: Solar panel area (cm^2)	η_{Ffc}	: Faradic PEMFC efficiency (%)
V_{WEL}	: Electrolyze output voltage (V)	$Q^C(H_2)$	: Consumed H_2 flow rate gas (ml/h)
E_{rev}	: Reversible voltage (V)	I_{Load}	: Load current (A)
V_{act}	: Activation overvoltage (V)	I_{HCS}	: HCS current (A)
V_{ohm}	: Ohmic voltage (V)	Δ_1	: Activation PES parameter
V_{con}	: Concentration overvoltage (V)	Δ_2	: Activation HGS parameter
I_{EL}	: Electrolyze input current (A)	Δ_3	: Activation HCS parameter
R	: Perfect gas coefficient (R=8.31 J.Kg-1.K-1)	ε_1	: Decision parameter
F	: Faraday constant (F=96485 C/mol)	ε_2	: Decision parameter
N_C	: Number of electrolyze cells	I_{HGS}	: HGS current (A)
S	: Electrolyze area (cm^2)	I_{Surplu}	: Excess PES output current (A)
$Q^P(H_2)$	: Produced H_2 flow rate gas (ml/h)	U_{UCap}	: Voltage of UCap(V)
η_{Fel}	: Faradic electrolyze efficiency	I_{UCap}	:Current of UCap (A)
$U_{UCap(in)}$	: UCap Initial Voltage(V)	$Q^S max$	: Maximum H_2 stored quantity (mol)
$C_{UCap:}$	: Capacitor of the C_{UCap}(F)	Q^S_{min}	: Minimum H_2 stored quantity (mol)
$R_{UCap:}$	:Resistor the C_{UCap}(Ohm)	Q^{ness}	: Necessary H_2 system amount (mol)

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