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Fuzzy Logic Optimization of a Centralized Energy Management Strategy for a Hybrid PV/PEMFC System Feeding a Water Pumping Station

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Abstract- This paper shows a developed fuzzy logic supervisor used to manage energy flow in a hybrid renewable energy system composed of a photovoltaic generator and a proton exchange membrane fuel cell. The hybrid installation is used to feed a pumping system used to store water in a tank in order to use it whenever needed. This system is widely used especially for agriculture purposes but batteries are used to maintain continuous water pumping when the solar irradiance quantity is not enough for the photovoltaic generator to provide needed power for the pumping system. The proposed solution guarantees continuous power production and water availability with the least possible costs thanks to the developed management strategy. The obtained results prove the efficiency of the studied technique in reducing fuel consumption by minimizing its utilization as maximum as possible and that continuous water pumping process is guaranteed.

Keywords Hybrid renewable energy system, energy management strategy, Fuzzy logic technique, photovoltaic generator, fuel cell, pumping system.

1. Introduction

Renewable energy sources (RESs) are considered as a reliable solution to overcome the major disadvantages of energy extraction from fossil sources (petroleum, coal, uranium,...etc) such as pollution, limited quantities and its unequal geographic distribution [1]. Among these RESs, the photovoltaic (PV) technology that consists in converting solar irradiations into electrical energy, is witnessing a rapid evolution and a worldwide expansion of its utilization thanks to the different advantages that it offers such as affordable price, low cost maintenance and high reliability which explains its use in different fields such as agriculture and industrial applications [2-6].

Despite of the benefits of PV energy production, it is still considered as very dependent on weather conditions, especially solar irradiations and ambient temperature, which makes it very vulnerable in stand alone or off-grid applications [7,8]. In recent literature, many studies present various solutions and suggest numerous configurations to overcome this problem [9-11]. Among these solutions, the use of storage devices and/or the use of a second source (hybridization of RESs) are the most presented ones [12,13].

Many studies presented electrical energy generation from hydrogen by using fuel cells (FCs) as a solution to have continuous power production (theoretically) [14-16]. This technology is considered as a RES only if hydrogen is generated by a non polluting way such as water electrolyses [17]. On another hand, unlike PV technology, power generation from hydrogen by FC mean is still considered as a very expensive solution. So, as long as hydrogen is provided to the FC, this latter will continue generating a high cost DC power but without any dependence on climate variation unlike PV technology which generates a low cost, but strongly dependant to weather conditions, DC power. This makes the dual use of PV and FC generators to provide power for an isolated system that is functioning in off-grid mode, a very complementary hybrid solution especially if an adequate management of energy generation is applied in order to reduce the working time of the FC which leads to reducing the hydrogen consumption costs [18].

For such energy management in hybrid sources solutions which includes FC generators, several techniques are used in order to manage the energy management in a way that insures the most possible reduction in hydrogen consumption. Among these techniques, many algorithms based on Artificial Intelligence (AI) methods were tested such as Fuzzy Logic technique, Artificial Neural Networks (ANN) technique and Genetic Algorithms (GAs). FL technique is chosen for the developed Energy Management Strategy (EMS) in this work thanks to its simplicity and high efficiency [19].

This paper is organized as follows:

- Section II: This section is divided into two parts where the first subsection is reserved for presentation and modeling of different hardware parts of the studied system and the second subsection details the proposed hybrid configuration and the energy management strategy.

- Section III: The proposed solution which presents an optimization by Fuzzy Logic technique is developed and tested by simulating its working performance based on different scenarios of solar irradiations and stored water level.

2. Description of the Studied System

The studied system is composed by two renewable energy sources which are a PV generator and a PEM Fuel Cell feeding a pumping station with water storage system. This system is controlled by an EMS which is developed to keep a predefined quantity of stored water ready to be used whenever needed even when solar irradiance is absent which makes the PV generator unable to provide enough power for the system in an economic way limiting the hydrogen consumption by the PEMFC.

This section is divided in two parts where the first subsection presents the studied generators and the pumping system while the second one deals with the different controllers integrated in the EMS.

2.1. Hardware Part

In this subsection, Different energy sources and the pumping system are presented and modeled.

2.1.1. Photovoltaic Generator:

In order to obtain desired power production, a PV generator is made by connecting several PV cells in series (to increase the generated voltage) or/and in parallel (to increase the output current). On the other hand, commercialized PV generators are made of a set of PV panels connected in parallel where each panel is formed by a several number of PV cells connected in series [20].

Figure 1 presents the equivalent electrical circuit of PV cell. This model is the most used one in literature and it is considered as a reliable model of a single PV cell because it includes two resistances to model different physical phenomena that might accurate due to current losses, contact resistance and other factors [21].

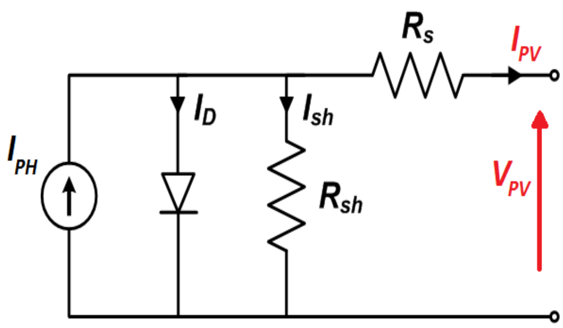


Fig. 1. Equivalent circuit of a single PV cell (1 diode model)

Based on the given cell model and on PV cell modularity principle, the overall expression of generated current by a PV generator is given by (1): [22]

$$I_{PV} = I_{Ph} - I_D - I_{Sh} \quad (1)$$

With:

$$I_{Ph} = N_P.[I_{CC}\frac{E}{E_r} + k_{iSC}(T - T_r)\frac{E}{E_r}] \quad (2)$$

$$I_D = N_P.I_s\left[\exp\left(\frac{V_{pv}}{N_S.V_T}\right) - 1\right] \quad (3)$$

$$I_{Sh} = \frac{V_{PV} + R_S I_{PV}}{R_{Sh}} \quad (4)$$

NP is the number of parallel strings and NS is the number of modules in series.

The PV generator used for this study is composed of Kaneka GSA-60 panels and mounted in order to obtain a generator with the characteristics presented in Table 1.

Table 1. Characteristics of the studied Kaneka PV generator

Parameter	Value
Np	2
Ns	5
Pmpp	600 W
Vmpp	335 V
Impp	1.8 A
Voc	460 V
Isc	2.38 A

2.1.2. PEM Fuel Cell:

Based on the works presented in [23], fig. 2 presents the electrical model of the PEMFC and (5) is the mathematical model of the generated voltage.

$$V_{FC} = E - V_{con} - V_{act} - V_{ohm} \quad (5)$$

Where:

- VFC : Fuel Cell Output Voltage (V).
- E : Theoretical Potential of the Cell (V).
- Vcon : Gazes Concentration Voltage Losses (V).
- Vact : Activation Voltage Losses (V).
- Vohm : Ohmic Voltage Losses (V).

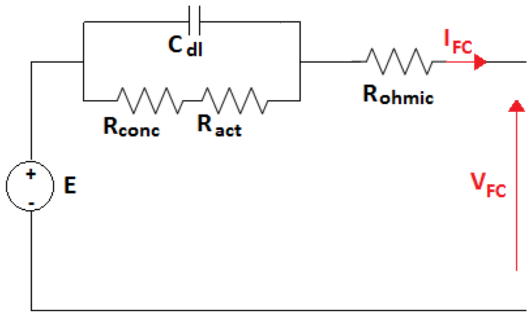


Fig. 2. Equivalent circuit of a PEMF fuel cell

Table 2 presents the PEFMC used for this study which is a 500W fuel cell commercialized by FuelCellsEtc.

Table 2. Characteristics of the chosen 500W PEMFC.

Parameter	Value
Rated Power	500 W
Number of Cells	24
Rated Performance	14.4V at 35A
Max Stack Temperature	60ºC
Hydrogen Purity Requirement	99.995 %
Start-Up Time	<= 30s

2.1.3. Water Pumping Station:

Generally, water pumping systems are composed of two parts: the first is composed by electrical motor and the second is composed by hydraulic components.

For electrical functioning principle of the studied station, a digital speed drive which is a 3 phased inverter used to convert the DC voltage into 3 phased voltages controlled in a way to adjust the speed of an induction motor coupled to it. For the hydraulic part, it is composed by a one directional centrifugal pump mounted to the motor (constituting a moto-pump set) and used to pump water from a first tank (used to simulate water source) to a second tank (used to simulate the reservoir).

Figure 3 is an equivalent presentation of the described pumping system and Table 3 presents its different characteristics.

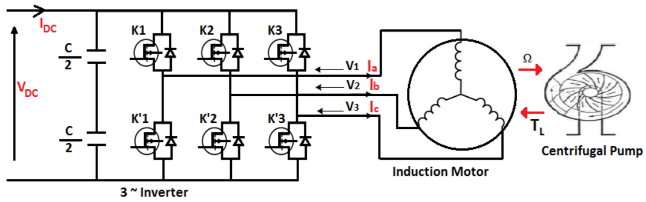


Fig. 3. Descriptive schematic of the different parts of the pumping system (Inverter + Induction machine + Centrifugal pump)

Table 3. Characteristics of the studied pumping station

Speed Drive	
Model	Moeller DV51
Maximum Power	2.2 KW
Maximum AC input	230 V
Maximum DC Input	400 V
Output Voltage	3 ~ 230 V
Moto-Pump	
Model	Ebara Pra-0.50T
Type of motor	3~ Asynchronous machine
Type of pump	Centrifugal pump
Power	3 Hp ≈ 0.37 Kw
Voltage	240 V
Nominal Current	1.8 A
Frequency	50 Hz
P	1
Cos ρ	0.8
Maximum Speed	2850 rpm ≈ 300 rad/s
Maximum Flow rate	45 L/min

Based on the electrical circuit of the inverter, the different currents can be related as in (6) and the output voltages can be modeled by (7). [24]

$$I_{DC} = K_1 I_a + K_2 I_b + K_3 I_c \quad (6)$$

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \frac{V_{DC}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} (7)$$

Based on [25], equations (8-11) present the rotor and stator voltages of the asynchronous machine in d,q frame.

$$V_{qs} = R_s.I_{qs} + \frac{d\phi_{qs}}{dt} (8)$$

$$V_{ds} = R_s.I_{ds} + \frac{d\phi_{ds}}{dt} (9)$$

$$V_{qr} = R_r.I_{qr} + \frac{d\phi_{qr}}{dt} (10)$$

$$V_{dr} = R_r.I_{dr} + \frac{d\phi_{dr}}{dt} (11)$$

Where :

ϕ_{qs} , ϕ_{ds} are the stator flux projections on d and q axes.

ϕ_{qr} , ϕ_{dr} are the rotor flux projections on d and q axes.

Equation (12) presents the mechanical model of the machine.

$$T_{em} - T_L - f\Omega = J\frac{d\Omega}{dt} (12)$$

Where:

f : Viscous friction coefficient (N.m.s)

J : Moment of Inertia (Kg.m2)

T_{em} : Electromagnetic torque (N.m)

Ω : Rotor speed (rad.s-1)

T_L : Load torque (N. m)

The load torque is directly related to the centrifugal pump and can be modeled by (13)

$$T_L = K\Omega^2 (13)$$

Where K is the torque constant of the pump.

The overall mechanical model of the Moto-Pump (MP) system becomes (14)

$$T_{em} - K\Omega^2 - f\Omega = J\frac{d\Omega}{dt} (14)$$

2.2. Software Part

In this subsection, the adopted EMS is presented and different controllers developed to maintain good performance of the system are detailed.

2.2.1. EMS Configuration and Working Principle:

The developed EMS is composed by local controllers and one central supervisor. Each local controller is communicating with the central one by sending different measurements such as generated power from both PV and PEMFC, water level at the second tank which will be used to compute the Moto-Pump (MP) power demand and Voltage variation at the DC bus level.

The central controller is developed by Fuzzy Logic Technique in order to compute reference power that must be delivered from each source and reference speed of the electrical machine. Local controllers receive these control signals and each one must supervise the proper functioning of the component related to it. Figure 4 is a descriptive schematic of this principle and shows power flow from each source through the DC voltage bus which is feeding the MP. All of this is realized via local controllers by receiving control signals from the central one.

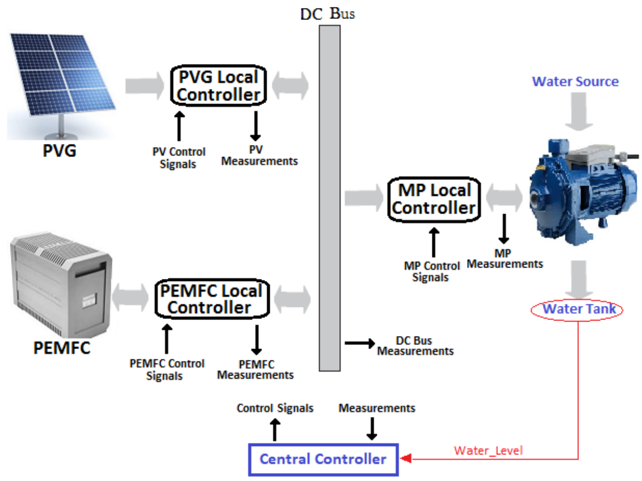


Fig. 4. System configuration and EMS working principle

2.2.2. Local controller of pumping station:

As explained in paragraph II.C, the voltage inverter is also used to control the speed of the induction machine, and tanks to the direct relation between the flow rate of the pumped water and the machine speed, the desired flow at the pump's outlet can be simply controlled by controlling the speed.

For this purpose, speed regulation is insured by using an improved Indirect Field Oriented Control (IFOC) technique which integrates a Fuzzy Logic speed controller.

This proposed IFOC-FL speed control system is detailed in Fig. 5.

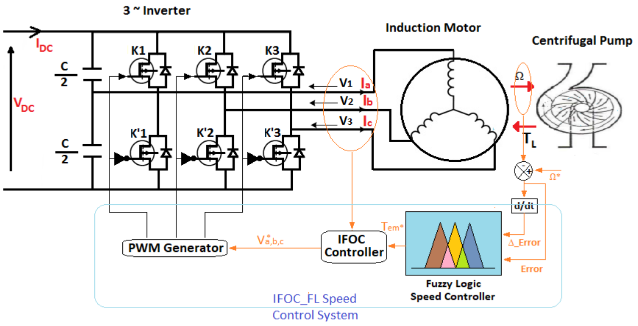


Fig. 5. Developed IFOC-FL speed contol system

Where:

- IDC and VDC are the current and voltage given by the DC Bus.

- V* and Tem* are the references of voltages and the electromagnetic torque.

- Ω and Ω* are the measured and the reference speed of the electrical machine.

- TL is the load torque applied by the pump on the electrical machine.

2.2.3. Local controller of PV generator:

Figure 6 explains the working principle of the developed local controller for PV generator. It shows that a DC-DC boost converter which is controlled by a Maximum Power Point Tracker (MPPT) is used based on the work in [26] in order to extract the maximum power from the generator taking account of weather conditions and load demand variations.

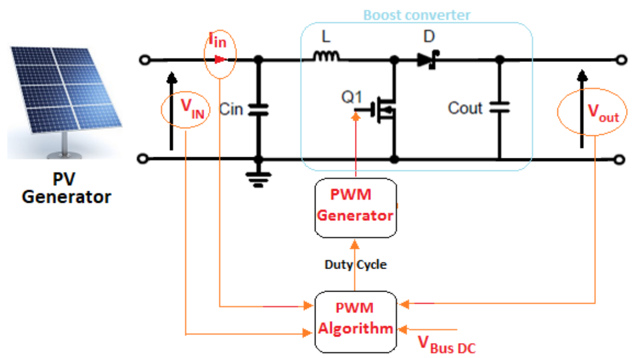


Fig. 6. MPPT system developed for the PV generator

2.2.4. Local controller of PEMFC:

Instead of extracting the maximum power from the fuel cell, the PEMFC local controller is used to extract only the missing amount of power in order to overcome power shortage when available PV power is less than the needed one computed by the central controller and to ensure that delivered voltage is equal to DC bus voltage.

Thus, and based on the presented work in [27], a PI controller for hydrogen supply is applied in order to control the generated power. A second controller is mounted at the output of the fuel cell in order to control the output voltage to meet the DC bus voltage by applying the Constant Voltage (CV) algorithm on a boost converter. This proposed concept is explained in Fig. 7.

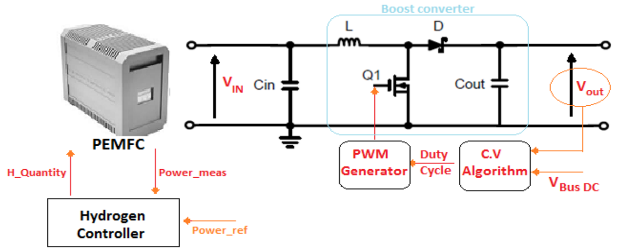


Fig. 7. Developed control system for the PEM Fuel Cell

3. Proposed Fuzzy Logic Solution

3.1. Working Principle

The central controller of the developed EMS, presented in Fig. 8, is composed of a different blocs used to treat the obtained measurements from different parts of the system in order to generate usable inputs for the Fuzzy Logic controller which will generate a set of control signals according to the available data.

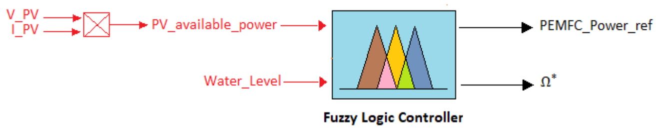


Fig. 8. Developed central controller

S.t:

- PV_available_power is the electrical power available by the PV generator measured at the output of the used boost converter and obtained by multiplying the measured voltage by the measured current.

- Water_level is the measurement of the water quantity in the storage tank and given between 0% and 100%.

The central FL controller is used to determine the optimal working state of the system based on the input variables. The two outputs of the controller are computed in a way to keep the hydrogen consumption as minimum as possible while taking into account the next two constraints:

- When the water level in the tank is less than 50%, the pump must work at its maximum regardless the sufficiency of available PV power → maximum speed reference (Ω*) must be generated and applied on the IFOC- FL speed controller and PEMFC must be used only as a complementary source.

- When the water level in the tank is greater than 50%, the generated PEMFC power reference must be kept at 0 → the generated speed reference (Ω*) must be adjusted according to the available PV power.

b) Detailed Configuration:

The classical method which is based on Mamdani technique as shown in Fig. 9 is used in building this Fuzzy Logic controller and it consists in dividing the controller on 3 phases as follows:

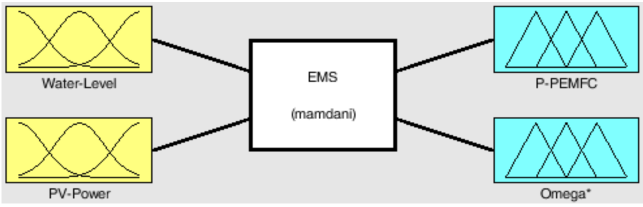


Fig. 9. Basic structure of a Mamdani FL controller

Fuzzification: During this phase, numerical values of input variables are converted into linguistic ones based on different fuzzy sets for each input predefined by the user.

The fuzzy sets developed for the input variables for this controller are given in Fig.10 and those developed for the output variables are given in Fig. 11.

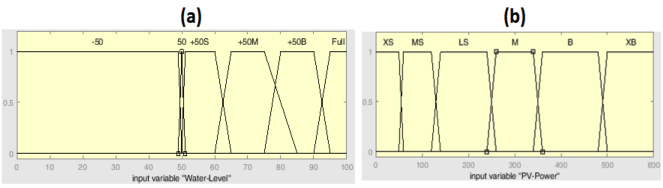


Fig. 10. Fuzzy sets for the input variables:
(a) Water level ; (b) Available PV power

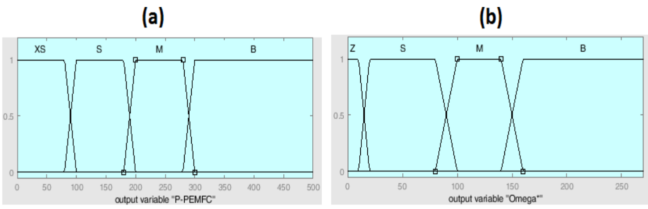


Fig. 11. Fuzzy sets for the output variables:
(a) Power reference for the PEMFC ; (b) Speed reference of the electrical machine

Inference Engine (IE): used to determine a linguistic output based on predefined rules which are determined by the user based on his experimental knowledge on the studied system.

Figure 12 shows the rules surface for the developed controller.

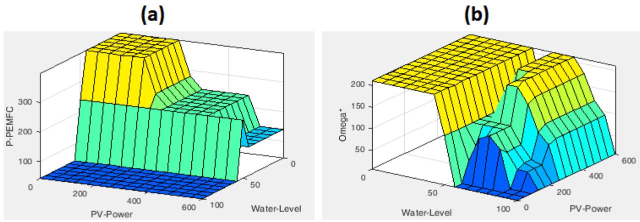


Fig. 12. Rules surface of each output variable in function of both inputs:
(a) Power reference for the PEMFC ; (b) Speed reference of the electrical machine

Defuzzification: This last phase consists in converting the linguistic solution generated by the IE into numerical value which presents the final decision or control signal of the FL controller.

The method used in this controller for this phase is called the gravity centre given by (15):

$$Value_{output} = \frac{\int_i \mu_i . VF_i}{\int_i \mu_i} \quad (15)$$

S.t:

- μ_i : degree of appurtenance.
- VF_i : fuzzy value.
- $Value_{output}$: output value.

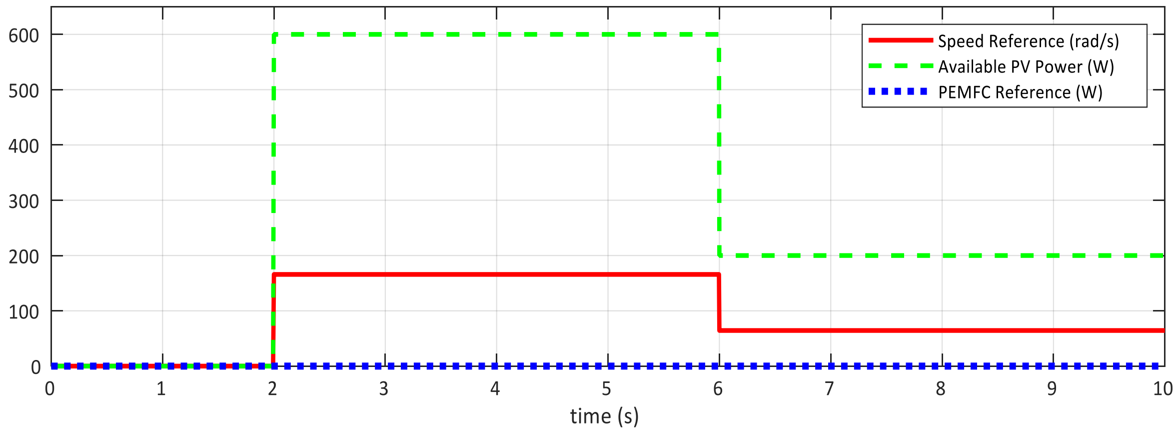
3.2. Result and Discussion

The different simulations shown in this section are realized based on different meteorological conditions and water level status in order to investigate the efficiency of the developed FL controller in different critical situations.

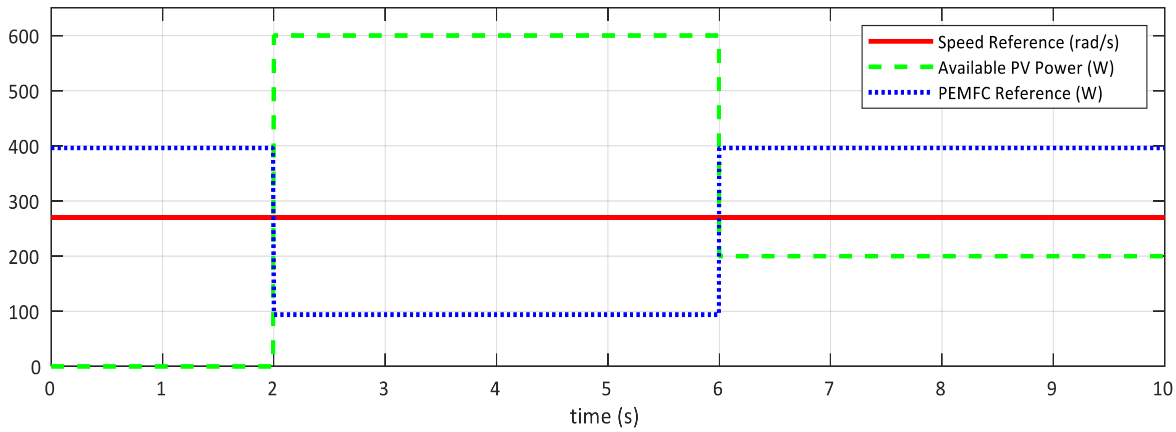
Figure 13 shows the obtained results when introducing a scenario of available PV energy with while maintaining the water level constant at 80% in a first place (Fig. 13.a) and at 30% in a second place (Fig. 13.b).

Figure 14 shows an inverse scenario obtained by varying the water level while the available PV power is maintained at a constant level equals to 500W in Fig 14.a and equals to 100W in Fig. 14.b.

Obtained results shown in Fig. 13 and Fig. 14 prove that the developed controller respects the predefined two constraints related to the water level by generating a speed control signal (270 rad/s) when the water in the tank is less than the half and by generating a 0 W power reference for the PEMFC when the water level is more than 50%. Also, it's obvious how the generated control signals vary according to the PV available power in each introduced scenario.

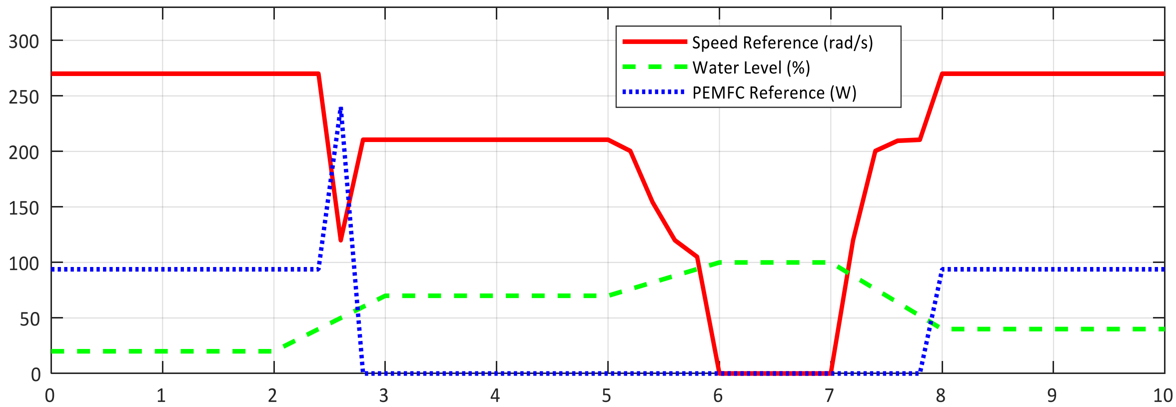


(a)

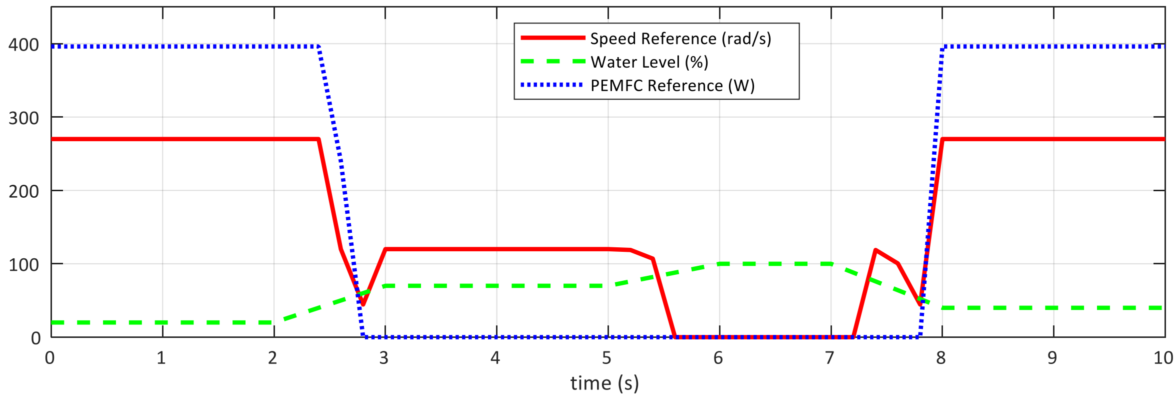


(b)

Fig. 13. Results with constant water level
(a) Water_Level = 80% ; (b) Water_Level = 30%



(a)



(b)

Fig. 14. Obtained results with constant PV power
(a) PV_Available_Power = 500 W; (b) PV_Available_Power = 100W

4. Conclusion

A centralized EMS for a HRES feeding an off-grid pumping system is developed and tested by simulating its efficiency in different conditions. The obtained results show that the developed central controller, which is based on FL technique, has successfully achieved the desired working performance of the system by minimizing the PEMFC use in order to decrease the hydrogen consumption as much as possible which has a major economical advantage while the two predefined constraints are respected at the same time. This is basically done by ensuring an intelligent management of the energy flow between the different sources in a way that guarantees maximum extraction of the available PV energy and its prior exploitation in powering the system instead of parallel use of the two sources.

As a future work, the performances of the proposed FL controller will be investigated in real time by implementing it on an embedded target such as STM32 or Arduino boards.

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