Efficient Design of a Hybrid (PV-FC) Water Pumping System with Separate MPPT Control Algorithm

Sami Ben Slama†, Abderrahmen Ben Chaabène†† and Adnane Chérif†††

†,†††Faculty of Sciences of Tunis El Manar, PB 2092, Belvedere, Tunisia
††Research Unit C3S, ESSTT, 5 Street Taha Hussein, PB 1007, Tunisia

Summary

In this paper, we propose an efficient design along with modeling and simulation of a small scale water pumping system fed by a hybrid Photovoltaic- Fuel Cell (PV-FC) power system. An overview of the basic theory of such system along with their modeling and simulation package is presented. A switching Maximum Power Point Trucking (MPPT) control algorithm is applied to the proposed configuration. The main goal is to extract the maximum power from each hybrid power system component, Photovoltaic (PV) generator and Fuel Cell (FC) source. Some simulation results are given.

Keywords:

Photovoltaic, Fuel Cell, Hybrid source, Control, Electrolyser, Tank, pump.

1. Introduction

The renewable energy sources (solar, wind, geothermal etc.) attract more attention as an alternative energy. Among the 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.

The Photovoltaic energy has been employed around the whole word in most recent years as the power source for pumping water during the day, making water available for domestic and irrigation uses [1].In addition, the advantage of using water pumps, powered by PV system include low maintenance, ease of installation, reliability and matching between the powers generated and the water usage needs. Therefore, the disadvantage of the purely PV energy is the intermittence of this source, depending with weather conditions and several factors such as the solar radiation, the temperature and the state of solar panels [2].In any case, one method to overcome this problem is to integrate the PV plant with other power sources such as Fuel cell [3]. It must be noted, that the PV-FC system includes solar panels and a Proton Exchange Membrane Fuel Cell (PEMFC) system working in parallel with an electrolyser and a storage tanks for the compressed hydrogen. If the solar radiation level is high enough, the PV array powers the load and the excess power is stored in hydrogen by the electrolyser. Otherwise, the fuel cell is switched on to generate electricity to complement any shortfall in solar radiation. The MPPT control technique was widely used in literature for only PV array to deliver continuously the highest power to the load when variations in irradiation and temperature occur [4]-[6]. The particularity of this work consists on the use of this technique to extract the maximum power from both of the two sources by an automatic switching. Thus, the PV-FC hybrid system output power becomes controllable.

The paper is organized as follows: In section 2, we describe the whole PV-FC autonomous water pumping system and we present the developed models of each part of this system. Section 3 deals with the Maximum Power Point Tracking control laws. In section 4, we illustrate the analysis of the simulation results.

2. Describing and Modeling of P-VFC pumping system

2.1 Design of the global system

In the studied system in Fig. 1, the photovoltaic array feeds the load directly. The excess solar is stored in chemical form. An electrolyser (EL) dissociates water in hydrogen and oxygen. The gas is stored without loss regardless of the storage time. When the solar array cannot provide the entire request for electricity, the fuel cell is connected. It regenerates the stored electricity by recombining hydrogen and oxygen. The Fuel Cell produces pure water which is stored to supply the electrolyser. This system is composed of a solar generator and an energy storage system. The latter is composed by an electrolyser, a storage unit of gases and a fuel cell [7]. Although, the storage system by hydrogen has a lower yield than that of batteries and the performance of the PV-FC system is increased by the total use of energy delivered by the photovoltaic array.

The detected variables are the photovoltaic current (I_{pv}), the photovoltaic voltage (V_{pv}), the fuel cell current (I_{FC}), the fuel cell voltage (V_{FC}), the buck converter output current (I_{out}) and voltage (V_{out}).

Manuscript received January 5, 2012
Manuscript revised January 20, 2012

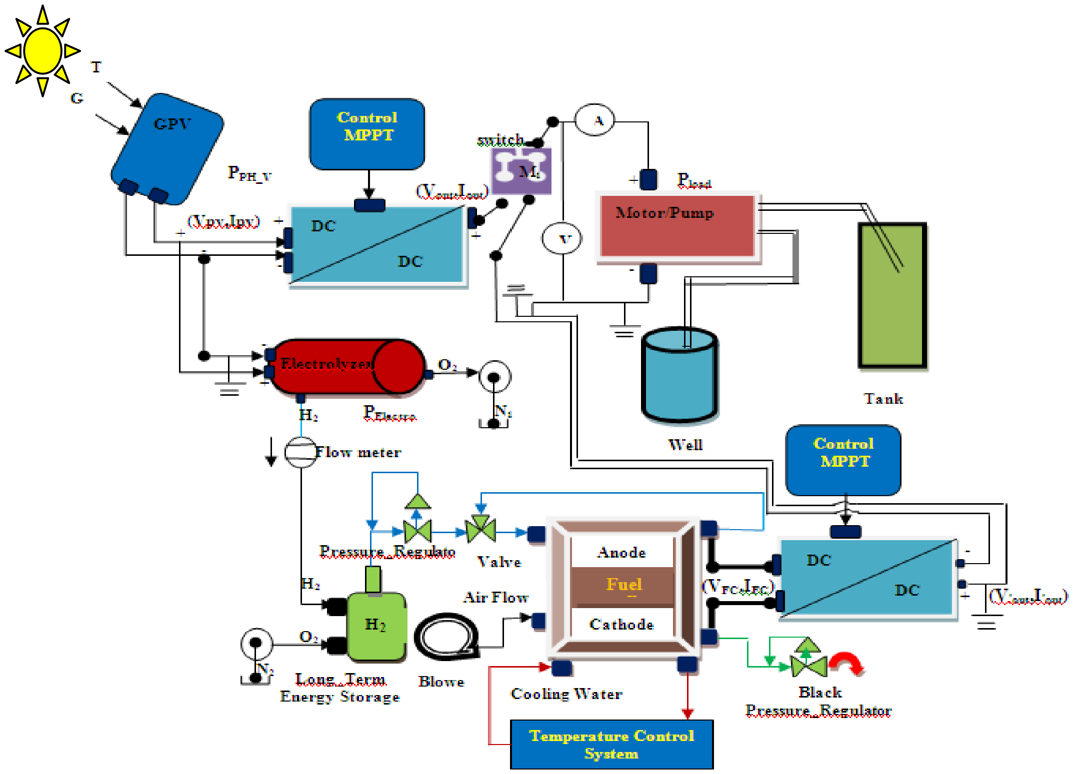

Fig. 1 PVFC hybrid water pumping system

2.2 Model of photovoltaic arrays

Based on a single exponential model of the electrical characteristics of a PV array (see Fig. 2), the nonlinear PV array can be modeled as Ip=f (Ipv, Vpv) [8]. It must be noted that, the standard test condition (STC) correspond to a sunning of 1000 W/m2, a cell temperature of 25 °C and a mass of air optics AM (Air Mass) equalizes to 1,5. This work has used the following global model of a solar cell which is described as follows.

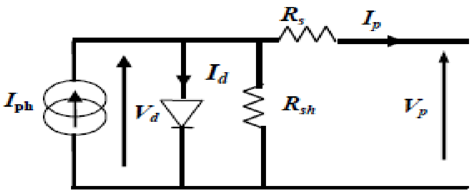

Fig. 2 Model of the PV array

The following classical equation of a PV cell describes the relationship between the current and the voltage of the cell, as in Eq. (1).

$$I_{pv} = I_{ph} - I_s\left[\exp\left(\frac{V_{pv}+R_s+I_p}{V_t}\right)-1\right]-\frac{V_p+R_s+I_p}{R_{sh}} \quad (1)$$

By neglecting the effect of R_S and R_{sh} we can rewrite I_{PV} as only a function of V_{PV} can be expressed in Eq. (2).

$$Ip = I_{ph} - I_s\left[\exp\left(\frac{V_p}{V_t}\right)-1\right] \quad (2)$$

With $I_{ph} = \frac{k_c G}{1000}$ and $V_t = \frac{n_t k_b T}{q}$

The parameters of this model are described in the Table1.

Table 1: Parameters description of the model

Parameter	***Description***
I_p	PV generator current, [A]
V_p	PV generator voltage, [V]
V_t	Thermodynamic potential, [V]
I_{ph}	Photo-Current, [A]
I_s	Saturation Current, [A]
K_c	Illumination Constant
G	Illumination, [W/m^2]
q	electron charge, [C]

2.3 Alkaline water electrolyser model

An actual alkaline water electrolyser, is a PEM type, consists of several electrolyser cells connected in series.

The electrolyser model, represented in Fig. 3, is based on the characteristics of individual cells. The calculations of the required operation voltage and the mass flow rates of hydrogen and oxygen are all done on a per cell basis, while the corresponding values for the whole electrolyser unit are simply found by multiplying by the number of series cells [9].

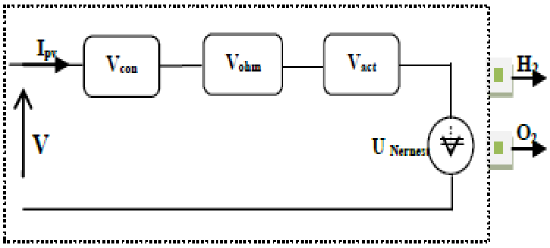

Fig. 3 Simplified circuit of the alkaline water electrolyser

The cell voltage of an electrolyser [10] is given by the following expression.

$$V_{actuel} = U_{Nernst} + V_{act} + V_{ohm} + V_{con} \quad (3)$$

The current density, expressed in Eq. (4), across an electrode is super imposed on the current due to the reaction Ox+ne<=>red-, which can be calculated by the Bulter- Volume relationship. So, the intensity is a function of voltage and intensity at the anode [11].

$$I = I_0\left[\exp(\frac{\alpha\sigma\eta F}{RT}) - \exp(\frac{(\alpha-1)\sigma v F}{RT})\right] \quad (4)$$

2.4 Gas Storage Tank model

The traditional way of storing hydrogen is to compress the gas in tanks. Since hydrogen behaves, very much, like an ideal gas in the ambient temperature (Fig.4).

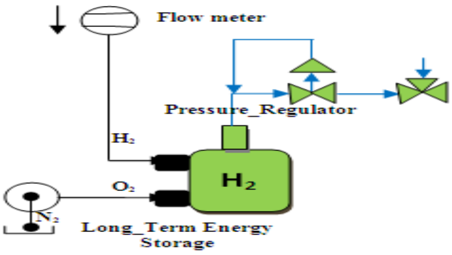

Fig. 4 Gas Storage Tank Model

Therefore, the mathematical model for the hydrogen pressure p in a storage tank can be calculated from Eq. (5) [12].

$$p = \frac{nRT}{V} \quad (5)$$

2.5 Polymer Electrolyte Membrane Fuel Cell Model

The PEMFC is known for a long time as a converter of hydrogen in energy (electrical + thermal) having very good efficiency research on this technology develop everywhere in the world in a considerable way. The reasons are well-known: the response to the environmental stresses (clean use), to the problems arising from the centralized production of electricity, the need for having energy alternatives (hydrogen vector) and certain technological requirements such as the applications space, underwater, electronic portable, power supply of isolated sites and Microsystems. It must be noted that, the choice of the technology of fuel cell with exchanging membrane of protons is done due to these interesting performances (weak weight, robust, solid electrolyte, fast starting, broad range of power of 1W to 10MW, etc.). It is thus significant to study this technology to be able to control it and extend its application. In addition, the characteristics of PEMFC are given by the following table 2.

Table 2: Characteristics of the PEMFC

Fuel Cell Type	***Operating Temperature***	***Typical Stack Size***	***Efficiency***	***Application***
Ploymer Electrolyte Membrane (PEM)	60-100°C Typically 80°C	<1KW-100KW	60% Transportation	Backup power, portable power. Distributed generation. Transportation Specialty vehicles.

Useful amount of electrical energy could be obtained from a fuel cell only when a reasonable current is drawn from it. The actual cell voltage (called V_{FC}) is lower than the theoretically voltage (called U_{th}) due to various irreversible loss mechanisms and it is represented by the Fig. 5 [9]. The cell voltage of a FC is expressed in terms of four terms which are represented as follows.

$$V_{actuel} = U_{Nernst} - V_{act} - V_{ohm} - V_{con} \quad (6)$$

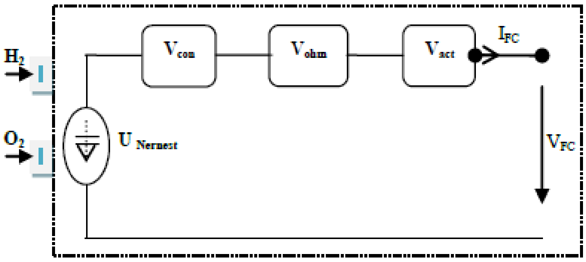

Fig. 5 The Fuel Cell Diagram

The instantaneous electrical power supplied by the cell to the load can be determined as in Eq. (7).

$$P_{FC} = V_{FC} \times I_{FC} \tag{7}$$

Where, V_{FC} is the cell output voltage for each operating condition, and P_{FC} is the output power. Moreover, the FC efficiency can be determined from Eq. (8):

$$\eta = \mu_f \times \frac{V_{FC}}{V_{MAX}} \tag{8}$$

μ_f is the fuel utilization coefficient, generally in the range of 95%, and 1.48 V which represents the maximum voltage.

2.6 Directly Current Motor

While it is not often that a load would be an actual resistor, Directly Current Motors (DC-Motors), such as those often used in PV-FC water-pumping systems, do exhibit a current–voltage relationship that is quite similar to that of a resistor. Most are permanent-magnet dc motors, which can be modeled as shown in Fig. 6. Notice that as the motor spins, it develops a back electromotive force e, which is a voltage proportional to the speed of the motor (ω) that opposes the voltage supplied by the PV-FC. From the equivalent circuit, the voltage–current relationship for the dc motor is given by Eq. (9).

$$V = IR_a + kw \tag{9}$$

Where *back emf* $e=k\omega$ and R_a is the armature resistance.
A DC-Motor runs at nearly constant speed for any given applied voltage even though the torque requirement of its load may change. For example, as the torque requirement increases, the motor slows slightly, which drops the *back emf* and allows more armatures current to flow. Since motor torque is proportional to armature current, the slowing motor draws more current, delivers more torque to the load, and regains almost all of its lost speed.

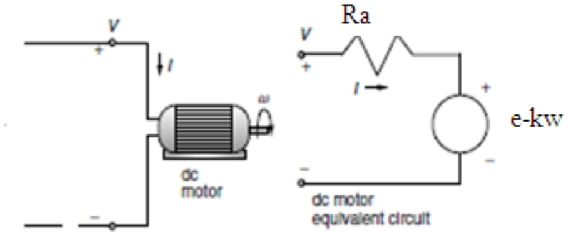

Fig. 6 Electrical model of a permanent magnet DC-Motor

2.7 The centrifugal pump

The flow head characteristic of a centrifugal pump is obtained making call to the laws of similarity [13]. In addition, the chart of the water quantity-head (Q-H) explains the different variations in the head of pumping, according to water quantity which forms bent charts. These latter are calculated as in Eq. (10).

$$\begin{cases} H = c_1.W^2 - c_2.W.Q - c_3.Q^2 \\ H = H_g + \Delta H \end{cases} \tag{10}$$

Where Q (m^3/s) is a Water quantity, Hg (m) is a geometric head, H (m) is a head and c_1, c_2 and c_3 are constants, depending on the pump dimensions. It must be noted that, the centrifugal pump torque (noted C_r), is assumed to be proportional to the square of the rotor speed. The C_r expression is given by Eq. (11).

$$C_r = k_p \left[1 - \frac{w_r}{w_s} \right] \times w^2 s \tag{11}$$

The characteristics values of the centrifugal pump are given by the following table.

Table 3: Characteristics Values of the centrifugal pump

Characteristics	***Values***
Flow rates	17.0L/min
Heads	30.0m
Voltage	12~30V DC
Rated maximum power consumption	150W
Power requirement	35W

3. MPPT Control approach of PV and FC Systems

The aim of the maximum power point tracking is to move the solar array operating voltage close to the maximum power point under changing atmospheric conditions in order to draw the maximum power from the array. So, the coupling of a load at constant power, without using battery, does not ensure an optimal operation. Then, it is essential to envisage an adapter of power to extract the maximum power from the PV-FC sources. The solar cell module can only provide this maximum at a specific voltage and current levels. So, for the PV-FC arrays there is an only point on its I-V curve in which the power is at its maximum value and for optimum utilization.

The equilibrium operating point of the PV-FC array should coincide with this point. In order to improve the performance of the PV pumping system, a DC-DC converter known as MPPT is used to match continuously the output characteristics of the PV-FC sources to the input of the load [14]. Therefore, the total amount of produced energy (PV generator, fuel cell, and storage output) must equal the total amount of consumed energy (user load, electrolyser, storage input, and losses) [15].Thus, the overall energy balance is given by Eq. (12).

$$P_{pv} + P_{FC} = P_{load} + P_{EL} + \sum_i P_i \tag{12}$$

The total power losses in the system are neglected. The power of the electrolyser and fuel cell are determined by the two followings equations:

$$P_{np\_el} = P_{STC,pv} + P_{\min,load} \tag{13}$$

$$P_{np\_FC} = P_{\max,load} \tag{14}$$

The principal control parameters of PV-FC are given by the following table:

Table 4: Principal control parameters of PV-FC

Parameters	***Description***
P_{PV}	PV generator output power, [W]
P_{FC}	Output power from PEM fuel cell, [W]
P_{Load}	user load power demand, [W]
P_{EL}	input power to alkaline water electrolyser, [W]
$\sum P_i$	Total power losses in the system, [W]
$P_{min, Load}$	minimum load power
$P_{max, Load}$	maximum load power
P_{np_el}	nominal power of electrolyser, [W]
$P_{STC,pv}$	Photovoltaic power in standard conditions.
p_T	Pressure inside the storage tank
p_{start}	Hydrogen tank pressure for turn-on operation of the fuel cell
t	The instantaneous time
t_{stop}	The final time of the simulation
Δt	The time step for the simulation
P_{np_FC}	Nominal power of fuel cell.

The control strategy of the PV-FC is based on different conditions. The first one, if $P_{PV} < P_{Load}$, $P_{Load} - P_{PV} \leq P_{np\_FC}$ and $p_T > p_{start}$ then $P_{Load} - P_{PV} = P_{FC}$. This condition means that the load is connected directly to the PV generator and the deficit power must be obtained from the auxiliary back-up generator system (i.e. the fuel cell). The second condition, if $P_{PV} > P_{Load}$ then $P_{EL} = P_{PV} - P_{Load}$. It means that the power from the PV generator is high enough to power the load, and the excess power is stored in hydrogen by the electrolyser. Finally, the last condition is if $P_{PV} < P_{Load}$ and $P_{Load} - P_{PV} > P_{np\_FC}$, then $P_{EL} = P_{PV}$. The latter condition means that the load and fuel cell are disconnected and the electrolyser is connected directly to the PV generator, until $p_T \geq p_{start}$ and $P_{Load} - P_{PV} \leq P_{np\_FC}$. So, the control of the strategy approach is given by the flowchart in Fig.8.

4. Simulations and results

4.1 MPPT law for PV source

The performance characteristics of a photovoltaic module depend on its basic materials, manufacturing technology and operating conditions as shown in Fig.9. However, an operating point of a photovoltaic module will move by varying solar radiation, cell temperature, and load values. For a given solar radiation and operating temperature, the output power depends on the value of the load. When the load increases, the operating point moves along the curve towards the right. So, only one load value produces a PV maximum power.

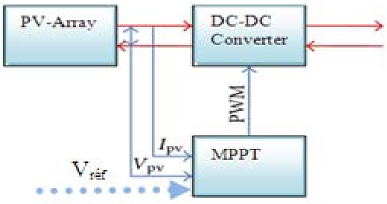

Fig. 9 MPPT Control Diagram of PV source

The principal outputs parameters are the voltage V_{out} and the current I_{out} which are given by Eq. (15).

$$V_{out} = \alpha V_{pv} \tag{15}$$

The maximum power points line, which is positioned at the knees of the I-U curves, has a nearly constant output voltage at varying solar radiation conditions. When the temperature varies, the maximum power points are generated in such a manner that the output current stays approximately constant (Fig. 10 and 11).

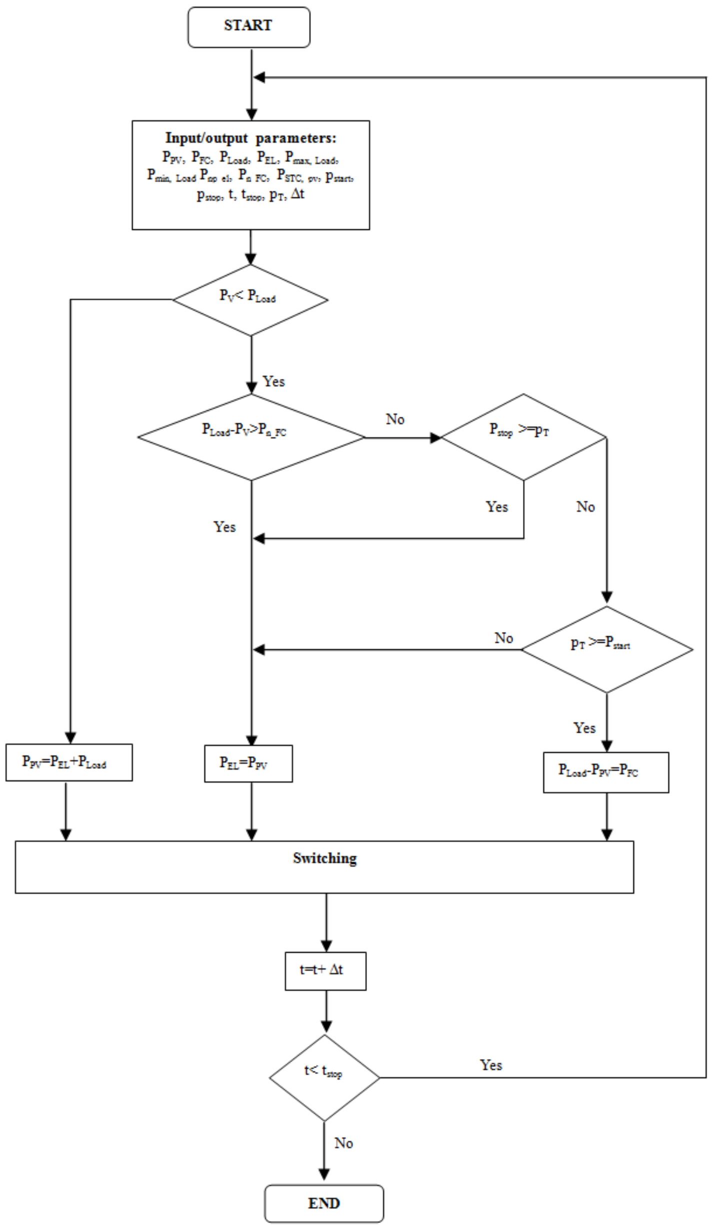

Fig. 8 The flowchart of the PV-FC system

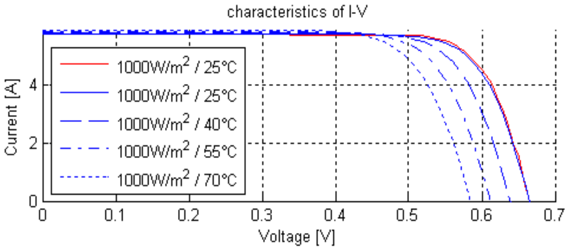

Fig. 10 PV-output current vs. Voltage for constant irradiation

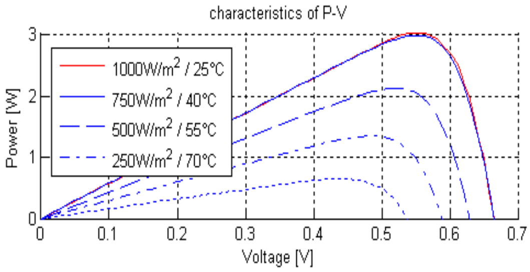

Fig. 11 PV-panel power vs. Voltage with variables irradiation and temperature

A Maximum power point tracking (MPPT) controller traces the MPP of FC using a MPPT algorithm. The controller generates instructions for a DC-DC converter and a certain amount of current which corresponds to MPP, is extracted from FC. There are several methods to search extreme value of a function [16]. In addition, the choice of the technology of fuel cell with PEM-FC is done due to these interesting performances (weak weight, robust, solid electrolyte, fast starting, broad range of power of 1W to 10MW, etc.). It is significant to study this technology to be able to control it and extend its application in Fig. 12.

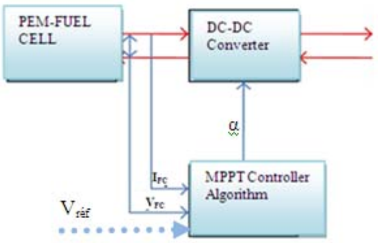

Fig. 12 MPPT Control Diagram of FC source

The principal outputs parameters are the voltage V_{out} and current I_{out} which are given by Eq. (16).

$$V_{out} = \alpha V_{pv} \qquad (16)$$

Where, the duty cycle α ϵ [0, 1] and the possible variables for controlling in a DC/DC converter are described in the table 5.

Table 5: Description of the output variables of MPPT law for Fuel Cell

Variables	***Description***
V_{PV}	Output voltage photovoltaic generator Input voltage DC/DC converter
I_{PV}	Output current photovoltaic generator Input current DC/DC converter
V_{out}	Output voltage DC/DC converter
I_{out}	Output voltage DC/DC converter

In order to analyze the performance of the proposed configuration, the system is tested and analyzed in two stages. At a first step, the system encounters the condition of a system variable. At a next step, the FC system is analyzed with constant parameters. The hypothetical step can be changed in FC system. Furthermore, the temperature T is applied to provide a variable FC operating condition. This step changes the temperature value from 40ºC to 80ºC. The V-I curve, of the FC system, for these temperatures are depicted in Fig.13.

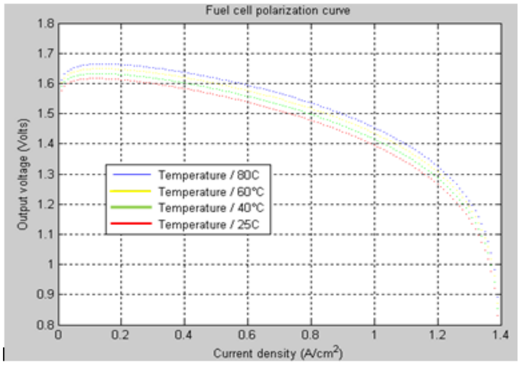

Fig. 13 FC-output voltage vs. Current density for different temperatures

The Fig. 14 illustrates the output voltage, the power curves and the maximum power point tracking for Fuel Cell. The Fig. 5 shows the increment of the voltage vs time with a constant average when the temperature increases.

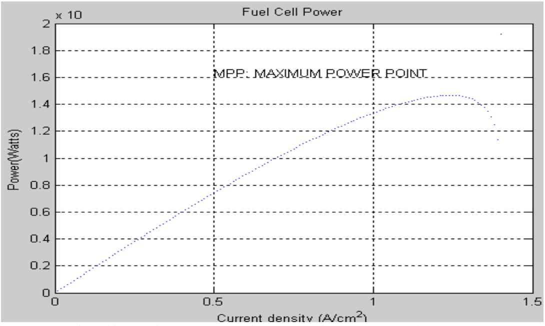

Fig.14 Fuel cell stack output voltage and power vs. its current curves operating temperature

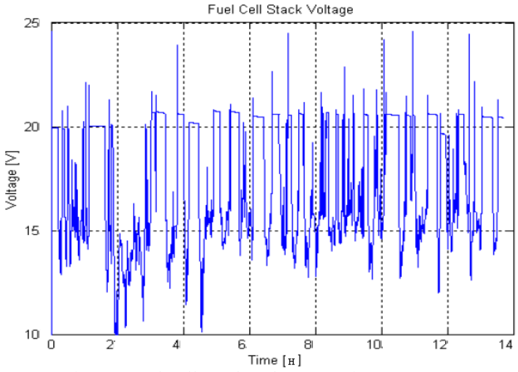

Fig.15. Fuel cell stack voltage vs. times curves

5. Conclusion

In this paper, we presented hybridization through combining photovoltaic and fuel cell energy sources in one supply system. The hybrid production unit offers the best possibility to use locally available renewable energies. The development of the different models and the use of the MPPT control strategy, for both of two sources, can always track the maximum power points of the hybrid sources. All the simulation results must be validated by the experimental studies that we are currently realized.

References

[1] Kim, I.S, Robust maximum power point tracker using sliding mode controller for the tree phase grid connected photovoltaic system. Solar energy, Vol. 81(Issue 3): 405–414, March 2007.

[2] P. Hollmuller, J.M. Joubert, B. Lachal and K. Yvon, Evaluation of a 5 kWp photovoltaic hydrogen production and storage installation for a residential home in Switzerland, International journal of hydrogen energy, Vol. 25(Issue 2):97–109, 2000.

[3] F.Valenciaga and P.F. Puleston, Supervisor Control for Stand-Alone Hybrid Generation System Using Wind and Photovoltaic Energy, IEEE Transactions on. Energy Conversion, Vol.20 (Issue 2):398–405, June 2005.

[4] B. Amrouche, M. Belhamel and A. Guessoum, Artificial intelligence based P&O MPPT method for photovoltaic systems, Revue des Energies Renouvelables (ICRESD), 11 – 16, 2007.

[5] N. Hamrouni, M. Jraidi and A. Chérif, Theoretical and experimental analysis of the behavior of a photovoltaic pumping system, Solar energy, Vol. 83 (Issue 8): 1335–1344, August 2009.

[6] G. Walker, Evaluating MPPT converter topologies using a MATLAB PV model, Journal of Electrical & Electronics Engineering, Vol .21 (Issue 1): 49-56, 2001.

[7] R. Chenni, Etude technico-économique d'un système de pompage photovoltaïque dans un village solaire, Ph.D. dissertation, Dept. Phy. Mentouri de Constantine Univ., Algeria, 2007.

[8] M. J. Case, M. J. Joubert and T.A. Harrison, A novel photovoltaic array maximum power point tracker, Power Electronics and Motion Control Conference, Cavtat & Dubrovnik, CROATIA September 2002.

[9] B. Soldi, I. Gökalp, A. Zeroual and A. Aymard, Modélisation d'une électrolyse d'eau à membrane polymère pour la production d'hydrogène", Revue des Energies Renouvelables, Vol. 12 (Issue 2) : 201–214, 2009.

[10] S. Ben slama, A. ben chaabene and A. chérif, Modeling and control of a photovoltaic –fuel cell hybrid water pumping system, The third International Renewable Energy Congress (IREC), pp.473-478, Hammamet, Tunisia, 2011.

[11] H. Choi, D.G. Bessarabov and R. Datta, A Simple Model for Solid Polymer Electrolyte (SPE) Water Electrolysis, Solid State Ionics, Vol. 175 (Issue 1): 535–539, 2004.

[12] Th. Bocklisch, H. Mehlich and J. Bard, Modeling, simulation and optimisation of a 2,5 kW PEM fuel cell system, Official proceedings of the International Conference Power Electronics, Intelligent Motion, Power Quality: PCIM Europe, pp.199-204, Nürnberg, Germany, June 2005.

[13] A. Saadi and A. Moussi, Etude de l'effet des fluctuations de température sur les techniques d'optimisation des systèmes de pompage photovoltaïque, CEE'2002, pp.232–237, Batna, Algeria, October 2002.

[14] M. Dargahi, J. Rouhi and M. Shakeri, Maximum Power Point Tracking for Fuel Cell in Fuel Cell/Battery Hybrid Power Systems. European Journal of Scientific Research, Vol. 25 (Issue 4): 538–548, 2009.

[15] Ch. DUMBS, Development of analysis tools for photovoltaic-diesel hybrid Systems, Ph.D. dissertation, Mines de Paris Univ., Paris, 1999.

[16] C. Wang, H. Nehrir and R. Shaw, Dynamic Models and Model Validation for PEM Fuel Cells Using Electrical Circuits, IEEE Transactions on Energy Conversion, Vol. 20, pp.442-451,USA, June 2005.

Ben Slama Sami received the engineer and master degrees, in Electronics, from Faculty of Sciences of Tunis (FST), in 2005 and 2009, respectively. He is a thesis student. His field of interest concerns the photovoltaic power, treatment water, neural network, Matlab and Bond-graph modeling.

Ben Chaabene Abderrahmen received the Doctorate degrees, from Faculty of Sciences of Tunis (FST), in Tunisia. He is a University Teacher in Electronics and Automatic. He is responsible of the Research Unit of Renewable Energies at The High Institute of Technologic Studies. His field of interest concerns the Renewable Energies Applications in water domain and Process control.

Cherif Adnane received the engineer, master and Doctorate degrees, from National Engineering School of Tunis (ENIT), in Tunisia. He is a professor in Electronics. He is a University Teacher in Electronics at Faculty of Sciences of Tunis (FST). He is responsible of the master specialty communication systems and networks. His field of interest concerns the photovoltaic power, digital signal processing, treatment water, neural network, Matlab and Bond-graph modeling.