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SOFC-PV System with Storage Battery Based on Cuckoo Search Algorithm

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Abstract: Each panel has an operating point (current, voltage) which allows it to deliver its maximum power. It is therefore necessary to try to control the choppers in order to stay as close as possible to the requested operating point. For this, we use the search algorithms for the optimal operating point (Maximum Power Point Tracker or MPPT). Lately, the MPPT technique has become the focus for a significant number of researches in order to improve the dynamic performance of the PV system, so we can distinguish several algorithms of the MPPT such as the P&O (Perturb & Observe) and those based on intelligent techniques such the meta-heuristic approach.

We will study and discuss in this work, the use of the Cuckoo Search (CS) algorithm to determine the maximum power point by using in the first section, the PV with a resistance load; in the second section, the same algorithm is used also to tune the PI controllers' gains of rotor speed and the DC-DC controller to adjust the DC Voltage coming from the PV/SOFC-Battery with an alternative load, in order to be able to supply the inverter which is connected to the induction motor and controlled by the Direct Torque Control (DTC), driving a centrifugal pump. The simulation results show the effectiveness of the proposed technique using the pumping system supplied by a hybrid source.

Keywords: *DTC; IM; hybrid SOFC-PV system; MPPT; battery storage; CSA.*

Mathematics Subject Classification (2010): 70Kxx, 93C10, 93-XX.

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1 Introduction

Optimization is a branch of mathematics, seeking to analyze and solve analytically or numerically the problems which consist in determining the best element of a set. Optimization methods are currently occupying a very important place in the scientific field given the complexity of industrial problems. The researchers thought about finding the solutions of these problems by flexible methods to integrate various specific constraints.

The algorithms of the first class are those of the conventional methods. These include the Newton-Raphson method, Nonlinear Programming (NLP), Quadratic Programming (QP), the Newton Method, Mixed Integer Programming and Dynamic Programming. All these mathematical methods are fundamentally based on the convexity of the objective function to find the minimum. According to the limits of conventional methods, the need to introduce new optimization techniques capable of overcoming the problem posed by classical methods is imperative. The methods which offer this possibility are the intelligent methods called "metaheuristic".

Metaheuristics are recently developed stochastic optimization methods. For this concern, numerous mathematical programming approaches for metaheuristic optimization have been proposed, for example, 'Particle Swarm Optimization' (PSO) is proposed by Kennedy and Eberhart [1]. They inspire the social behavior of swarming animals such as flocks of birds and schools of fish. An individual in the swarm has only local knowledge of his situation in the swarm. It uses this local information, as well as its own memory, to decide where to move. Ant Colony Optimisation (ACO) is proposed by Dorigo [2], it results from the observation of social insects, especially ants, which naturally solve complex problems. This ability is found to be possible due to the ability of ants to communicate with each other indirectly, by depositing chemicals on the ground which are called pheromones. This type of indirect communication is called stigmergy. We have also the artificial bee colony (ABC) proposed by Dervis Karaboga [3], genetic algorithms (GA) proposed by Holland [4] and the Bat algorithm proposed by Xin-She Yang [5], etc. In a difficult energy context, marked by the foreseeable exhaustion of fossil fuels and their impacts on the environment, expectations in terms of renewable energies in general and solar energy in particular, are increasingly important. These energies and, more particularly, solar energy are considered to be the future energy solution. Indeed, solar energy is one of the most environmentally friendly energy, an economical and sustainable source. Lately, the MPPT technique has become the focus for a significant number of researches in order to improve the dynamic performance of the PV system, mainly in terms of the ability to rapidly pursue the global power point (GMPP) in the presence of other local maximums power point (LMPP). Researchers have been interested in another type of the MPPT technique which is based on the meta-heuristic approach, for example, the MPPT-ABC [6], MPPT-GA [7] and MPPT-ACO [8].

The CS algorithm was first proposed by Yang and Deb [9], the Cuckoo Search (CS) is a recent metaheuristic which is inspired by the mode of reproduction of certain species of cuckoos. In fact, their reproduction strategy is unique in that the females lay their eggs in the nests of other species (whose eggs look similar). These eggs can then be incubated by surrogate parents. On the other hand, when cuckoo eggs manage to hatch in the host nest (they hatch faster), cuckoo chicks have the reflex to eject the host species eggs out of the nest and even mimic the call of the host chicks, for the purpose of being fed by the host species. However, it can happen that cuckoo eggs are discovered; in this case, the surrogate parents remove them from the nest, or abandon the nest and start their brood elsewhere. This meta-heuristic is therefore based on this parasitic behavior of cuckoo species associated with a “Levy flight” type of movement logic specific to certain birds and certain species of flies.

This work proposes the use of the cuckoo search algorithm to track the MPP and get the desired DC Voltage needed later by using the boost coverter, so the first part proposes the PV as a source and resistance as a load. In the second part, we propose the CS algorithm to tune the gains of PI controllers of speed and the DC-DC Voltage controller connected to the battery of hybrid system (SOFC-PV with storage battery), so we have the hybrid system as a source and the induction motor driving a centrifugal pump as a load.

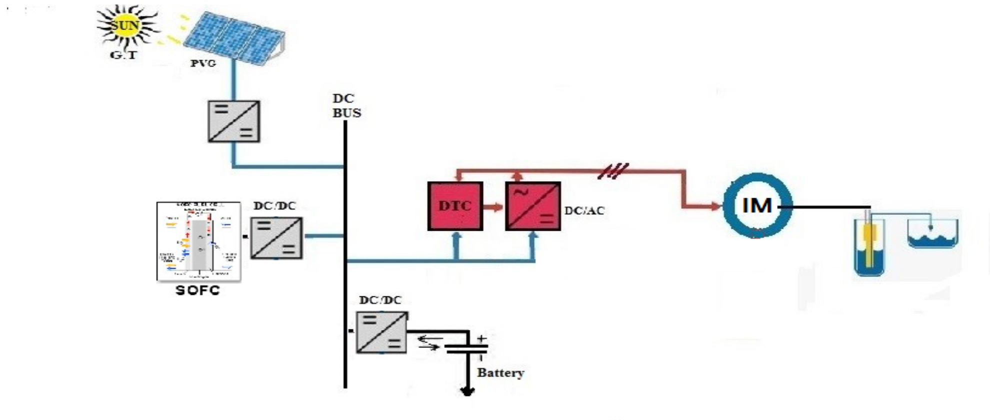

Figure 1: Scheme of SOFC-PV with a storage battery for the pumping system.

2 PV Module

Solar panels are intended to recover energy from solar radiation to transform it into heat or electricity. PV modules (usually presented in the form of panels) consist of a number of elementary cells placed in series in order to make the voltage at the output usable. These modules are then associated in a network (series-parallel) so that to obtain the desired voltages / currents. An equivalent circuit model for a solar cell is shown in Figure 2. The model consists of a current source, a diode, a shunt resistor R_P and a series resistance R_S.

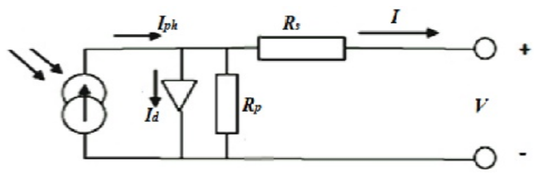

Figure 2: PV cell model.

The topology of the boost converter is shown in Figure 3. For this converter, the output voltage is always higher than the input PV voltage. Power flow is controlled by the on/off duty cycle of the switching transistor. This converter topology can be used in conjunction with lower PV voltages. No extra blocking diode is necessary when the boost topology is used. For sizing a photovoltaic system, we need to know first the motor consumption energy (as in our case we need to get Udc=514V). Then, we must take into account the obtained results and also the meteorological data as the input parameters of the photovoltaic installation of the input program.

The data sheet information on the PV panel is presented in Table 1. The commercialized solar modules are formed generally by a number of cells assembled in parallel N_p or /and in series N_s . The relationship between the cell terminal current and voltage is given by

$$I = I_{ph} + I_0\big[\exp(\frac{V + I.R_s}{\alpha.V_{th}} - 1)\big] - \frac{V + I.R_s}{R_p}, \tag{1}$$

where V_{th} is the thermal voltage of the cell, I_{ph} is the photocurrent, it depends mainly on the radiation and cell's temperature.

3 MPPT Based on Cuckoo Search Algorithm

Both P&O and INC algorithms may have difficulty in finding the optimum when used in large arrays where multiple local maxima occur [9]. In this section, we propose a cuckoo search algorithm to track the maximum power point. A boost converter, or parallel chopper, is used when it is desired to increase the available voltage of a DC source by controlling the duty cycle of the switching transistor. In photovoltaic systems, this converter can be used as a source-load adapter, when the operating point in direct coupling is on the right-hand side of the MPP.

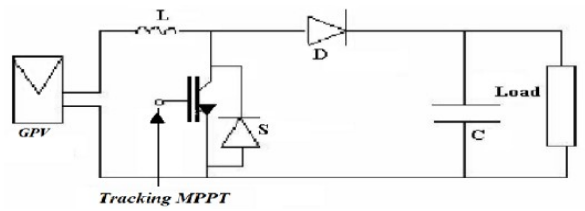

Figure 3: Boost Converter DC/DC.

3.1 Cuckoo Search principle

The Cuckoo Search (CS) algorithm is based on the following rules:

- Each cuckoo lays only one egg at a time and places it in a randomly chosen nest.
- The best nests with high quality eggs (solutions) are kept for the next generations.
- The number of host nests is fixed and the egg laid by a cuckoo can be discovered by the host species with a probability $P_a \in [0, 1]$. In this case, the host bird either takes the egg out of the nest or leaves the nest and builds a new one.

To simplify, this last hypothesis can be approached by replacing a fraction Pa of nests with new ones. In CS, each egg in a nest represents a solution and each cuckoo can lay a single egg, the goal is to use the new and potentially better solution to replace a poorer solution in a nest. Although the algorithm can be extended to a more complex case where each nest contains several eggs representing a set of solutions, here we use a simpler version where each nest contains only one egg. In this case, there is no longer any distinction between the egg, nest or cuckoo, and each nest corresponds to an egg which also represents a cuckoo.

3.2 Levy Flight

In the context of CS, the cuckoo movement pitch is determined by the Levy Flight (Figure 4). The Levy flight is a random walk in which the steps have a length having a certain probability distribution (Levy distribution), the direction of the steps being isotropic and random. The Levy Flight is a class of random walk in which the jumps are distributed according to the Levy distribution which consists of a power law with an infinite variance and a mean of the type: $Levy(\beta) \sim (y) = x^{-\beta}, 1 < \beta < 3$.

In the case of CS, the use of the Levy Flight improves and optimizes the search: new solutions are generated by a random Levy walk around the best solution obtained so far, which speeds up the overall search. From an implementation point of view, generating

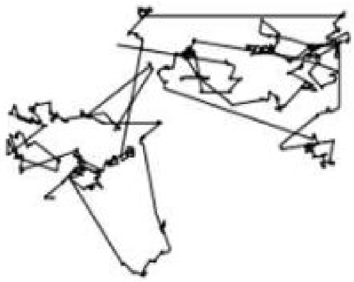

Figure 4: Levy Flight.

a random number with the Levy Flight follows two steps: choosing a random direction and generating the step that should obey the Levy distribution. The generation of a direction can be achieved from a uniform distribution, while the generation of steps is more delicate. There are several methods to achieve this, but one of the simplest and most efficient is to use Mantegna's formulas to determine the step s:

$$s = \frac{u}{|v|^{\frac{1}{\beta}}}. \tag{2}$$

3.3 MPPT-CSA

In general, the Lévy flight is characterized by using the following relation:

$$x_j^{i+1} = x_j^i + \alpha \oplus Levy \tag{3}$$

and the operator $\oplus$ represents the entry-wise multiplication [10] for the multidimensional problem. For MPPT, it can be simplified to

$$D_j^{i+1} = D_j^i + \alpha.Levy = D_j^i + s, \tag{4}$$

where

$$s \approx k.\frac{u}{|v|^{\frac{1}{\beta}}}(D_{best} - D), \tag{5}$$

where u and v are the centered Gaussian distributions such that

$$u = N(0, \delta_u^2), \quad v = N(0, \delta_v^2) \tag{6}$$

with

$$\delta_u = [\frac{\gamma(1+\beta) \times \sin\pi \times (\frac{\beta}{2})}{\gamma(\frac{1+\beta}{2}) \times \beta \times 2^{\frac{\beta-1}{2}}}]^{\frac{1}{\beta}}. \tag{7}$$

Figure 5 represents the schematic diagram of the DC-DC converter of a Photovoltaic panel using the MPPT based on the Cuckoo Search Algorithm and connected to the resistance load.

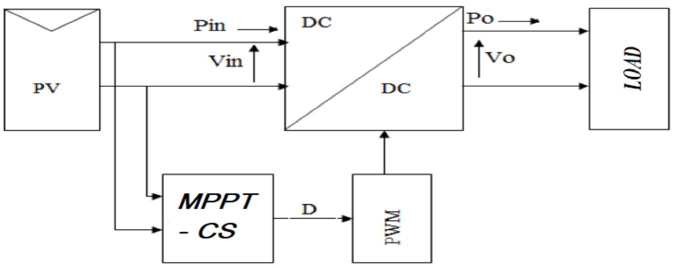

Figure 5: MPPT based on the Cuckoo Search Algorithm.

4 Solid Oxide Fuel Cell

The electrolyte must be an electronic insulator and an ionic conductor. It can be either liquid or solid. The bipolar plates allow the access of gases to the reaction sites by the presence of channels.

There are six types of fuel cells which, depending on the electrolyte, operate at different temperatures. They are the Alkaline Fuel Cell (AFC), Proton Exchange Membrane Fuel Cell, Direct Methanol Fuel Cell (DMFC), Phosphoric Acid Fuel Cell (PAFC), Molten carbonate battery (MCFC Molten Carbonate Fuel Cell), Solid Oxid Fuel Cell (SOFC (this type is used in our work)) as shown in Figure 6.

Fuel cells therefore allow the direct transformation of the chemical energy of the reaction of a hydrogen fuel with an oxidant oxygen into electrical energy. The electrical energy comes from the electronic exchange of the chemical reaction and not from the heat given off by the latter. To do this, two compartments containing the oxidant and the fuel, respectively, are produced on either side of the electrolyte, thus avoiding the mixing of the gases and therefore, the direct chemical reaction.

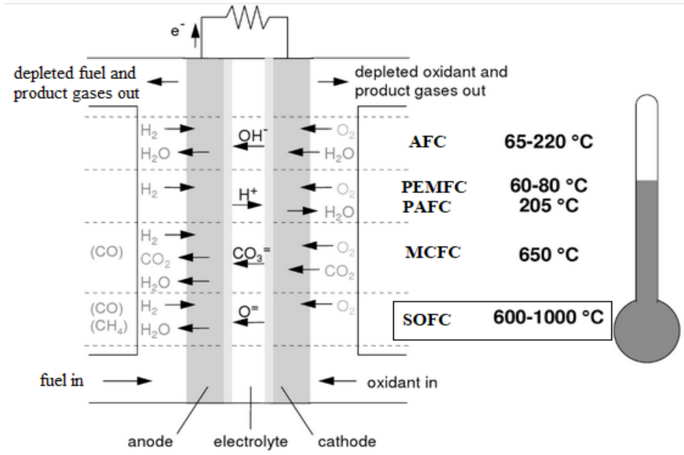

Figure 6: Fuel cells types; their reaction and operation temperatures [11].

On both sides of the electrolyte in each gas compartment, electrodes are arranged, which at the same time ensures the transport of electrons and ionic species (Figure 6). The fuel cell stack is composed of numerous single fuel cells in a series. Thus, the total voltage of the stack is approximately equal to the sum of every single cell voltage [12].

Reactions occurring in the SOFC are as follows [13].

Reforming reactions

$$CH_4 + 2H_2O \longleftrightarrow CO_2 + 4H_2, \tag{8}$$

$$CH_4 + H_2O \longleftrightarrow CO + 3H_2. \tag{9}$$

Water-gas shift reaction

$$CO + H_2O \longleftrightarrow CO_2 + H_2. \tag{10}$$

Electrochemical reactions. Anode

$$H_2 + O^{-2} \longrightarrow H_2O + 2e^-, \tag{11}$$

$$CO + O^{-2} \longrightarrow CO_2 + 2e^-. \tag{12}$$

Cathode

$$\frac{1}{2}O_2 + 2e^- \longrightarrow O^{2-}. \tag{13}$$

5 Direct Torque Control (DTC)

The direct torque control has many advantages that are already well known over conventional techniques: the fast torque response; it is considered as a sensor-less control, robust against the variation of machines parameters; relatively simple without the Park transformation and without pulse width modulation (PWM). It also allows decoupling between the control of the flux and the torque. Thus, several research works have been developed for the application of this technique to synchronous and asynchronous machines.

The first application of the DTC to the asynchronous machine appeared in the 1985s, and was proposed by Takahachi and Bepenbrock [14]. The stator flux vector can be estimated using the measured current and voltage vectors [15–17]

$$\frac{d\varphi_s}{dt} = V_s - R_s I_s \tag{14}$$

or

$$\varphi_s = \int (V_{s-} R_s I_s)\, dt. \tag{15}$$

The DTC is based on the use of the hysteresis controllers, to control the estimated stator flux and electromagnetic torque. These two variables are controlled by a hysteresis controller with two levels.

The output of the comparators and the stator flux angle are used to index a switch table of optimum voltage vectors in order to determine the suitable voltage vectors. The sector of the stator flux is divided into six sectors. It indicates that the appropriate voltage vector should be chosen in a particular sector, either to increase the stator flux or to decrease the stator flux and either to increase torque or to decrease torque.

6 Pumping System

The proposed hybrid system is shown in Figure 1. The battery is also connected to dc link through a DC-DC converter. Figure 7 represents the controller of a DC-DC converter used to maintain the dc voltage constant that is needed to feed our pumping system.

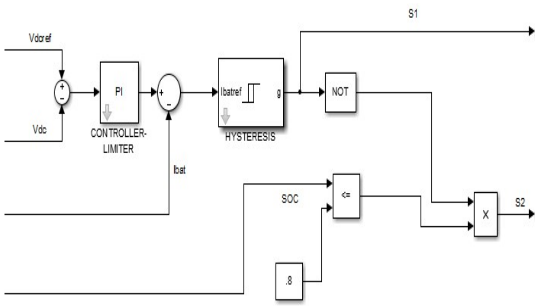

Figure 7: DC-DC Converter Controller.

7 Battery Storage

The battery control is an essential element for the success of autonomous systems. The batteries used in autonomous systems are generally of the lead-acid (Pb) type. Cadmium-nickel (NiCd) batteries are rarely used anymore because their price is much higher and they contain cadmium (toxic). Their replacements, nickel-metal hydride batteries (NiMH) are interesting and used in this paper.

Treating the controller output as the reference current for the battery, a hysteresis band approach is adapted to switch either Q1 or Q2 of the DC-DC converter as shown in Figure 8.

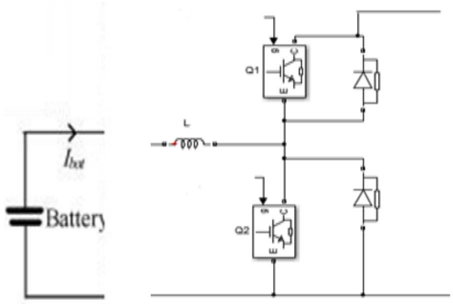

Figure 8: Controller battery.

In this work, the battery acts as a source or sink, the depth of discharge is equal to 60%.

8 Tuning PI Gains by Cuckoo Search Algorithm

The input of our PI controller is used the error calculated by the difference between the reference and instantaneous values (e1=w*-w) of the PI speed controller and (e2=Vdc*-Vdc) of the PI-DC Voltage source. The PI controller for the above system can be presented as the following expression

$$u = k_p e(t) + k_i \int e(t)dt. \tag{16}$$

Cost-function is presented by calculation of the error between the reference and estimated values; and the numbers of iterations and population used in this work are the same; it=50, Npo=15.

9 Digital Simulation

The pumping system is built using MATLAB/SIMULINK. In this simulation, the induction machine parameters are listed in Table 2. The centrifugal pump performances used in this work for speed of 2900 tr/min are: Q=30 m $^3/h$, H=80m, P=1.5 KW. SOFC with 200 cells in a series. We observe the performance of the proposed supply system with 11 PV solar panels to get 514V.

10 Discussion of Results

In the first part, as shown in Figure 9, the DC Voltage and Duty Cycle responses (of the output of the DC-DC converter connected to the resistance load) are presented using the system presented in Figure 5. In the second part, we propose to add a SOFC with a storage battery to supply an alternative load (IM-Pump). The pumping system is simulated with constant load torque (10N.m) applied between 0.6sec and 0.8 sec and the variation of irradiation and temperature as shown in Figure 10, and a simulation was run in a closed loop as shown in Figures 10 and 11, where it can be observed that the DC Voltage, flux and rotor speed track their references (Vdc*=514V, Flux*=1.1Wb, w*=126 rad/ sec). To get the disired value of voltage, we have used 11 panels.

The nominal open-circuit voltage	42.1V
The nominal short-circuit current	3.87A
The voltage at the MPP	33.7V
The maximum experimental peak output power	120W
The current at the MPP	3.56A
The open-circuit voltage/T° coefficient	$(8\,0 \pm 10)mV\%C°$
The short circuit current/T° coefficient	$(0065 \pm 0.015)mV\%C°$
Parallel resistance Rs	0.473Ω
Serie resistance Rp	1367Ω

Table 1: Data sheet information on the PV panel "BP MSX120".

Power	3.5Kw
Stator resistance	4.85 Ohm
Rotor resistance	3.805 Ohm
Inertia	0.031Kg.m ^{2}
Friction	0.001136
Frequency	50 Hz
Stator inductance	0.274H
Rotor inductance	0.274 H
Mutual Inductance	0.258 H
Poles	2

Table 2: Data sheet information on the Induction Motor.

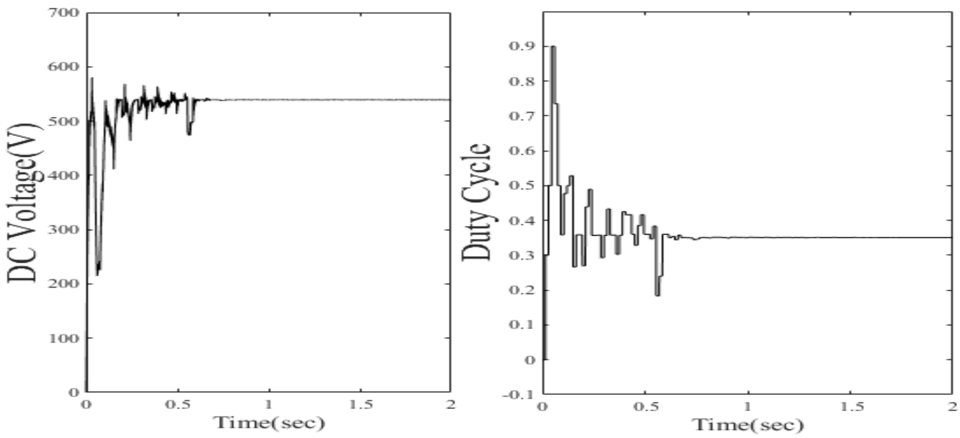

Figure 9: DC Voltage response using PV connected to the resistance load and based on the MPPT-CS method (G=1000W/m ^{2}, T=298K).

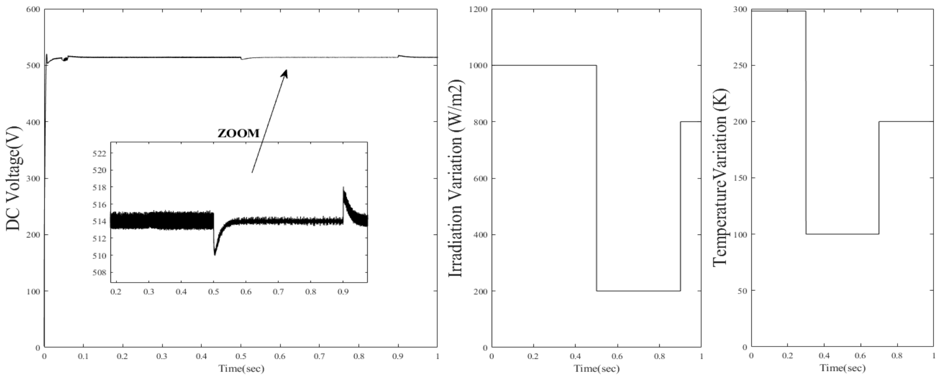

Figure 10: DC Voltage response using a Hybrid System (PV-SOFC-Battery-IM-Pump) based on the CS method with irradiation, temperature and torque variation.

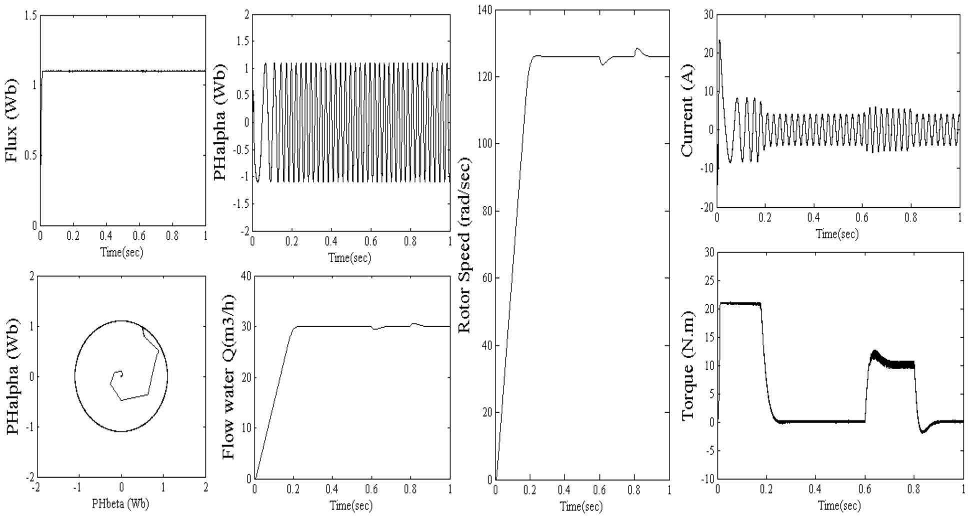

Figure 11: Current, Flow of water, Flux, Torque and Rotor Speed responses of a hybrid (PV-SOFC-battery-IM-Pump) System based on the CS method with irradiation, temperature and torque variation.

11 Conclusion

The aim of this study is to resolve the drawback of power loss caused by oscillations around the maximum power point (MPP) and the relatively low response time to rapid changes in weather conditions. This paper proposes another type of the control named a meta-heuristic algorithm (Cuckoo Search Algorithm), which is used on one hand to track the maximum power point, and on the other hand, the same metaheuristic algorithm is used to tune the PI gains to get the desired value that we need to supply our system

(514V). The obtained simulation results show the effectiveness of the proposed algorithms using in the first section the load resistance supplied by PV and in the second part the indution motor driving pump fed by a hybrid system.

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