Maximum Power Point Tracking of a Photovoltaic System using a Fuzzy Logic Controller on DC/DC Boost Converter

M. T. Makhloufi [1], M. S. Khireddine [2], Y. Abdessemed[3] and A. Boutarfa[4]

**[1] University of Batna, Electronics Department, LEA Lab.
Batna, Algeria**

**[2] University of Batna, Electronics Department, LRP & LEA Labs.
Batna, Algeria**

**[3] University of Batna, Electronics Department, LRP Lab.
Batna, Algeria**

**[4] University of Batna, Electronics Department, LEA Lab.
Batna, Algeria**

Abstract

The solar photovoltaic power has received great attention and experienced impressive progress the countries all over the world in recent years because of more and more serious energy crisis and environmental pollution. Due to scarcity of fossil fuel and increasing demand of power supply, we are forced to utilize the renewable energy resources. Considering easy availability and vast potential, world has turned to solar photovoltaic energy to meet out its ever increasing energy demand. The mathematical modelling and simulation of the photovoltaic system is implemented in the MATLAB/Simulink environment and the same thing is tested and validated using Artificial Intelligent [1].
This paper proposes an intelligent control method for the maximum power point tracking (MPPT) of a photovoltaic system under variable temperature and solar radiation conditions. This method uses a fuzzy logic controller applied to a DC-DC boost converter device. A photovoltaic system including a solar panel, a DC-DC converter, a Fuzzy MPP tracker and a resistive load is modeled and simulated. Finally performance comparison between fuzzy logic controller and Perturb and Observe method has been carried out which has shown the effectiveness of fuzzy logic controller to draw much energy and fast response against change in working conditions.

Keywords: *solar energy; photovoltaic; PV; MPPT; P&O; Boost converter; fuzzy logic; optimization.*

1. Introduction

Energy has the great importance for our life and economy. The energy demand has greatly increased due to the industrial revolution. Significant progress has been made over the last few years in the research and development of renewable energy systems such as wind, sea wave and solar energy systems. Among these resources, solar energy is considered nowadays as one of the most reliable, daily available, and environment friendly renewable energy source [2], [3].

However, solar energy systems generally suffer from their low efficiencies and high costs [4]. In order to overcome these drawbacks, maximum power should be extracted from the PV panel using MPPT techniques to optimize the efficiency of overall PV system. MPPT is a real-time control scheme applied to the PV power converter in order to extract the maximum power possible from the PV panel. The MPPT working principle is based on the maximum power transfer theory. The power delivered from the source to the load is maximized when the input resistance seen by the source matches the source resistance.

Therefore, in order to transfer maximum power from the panel to the load the internal resistance of the panel has to match the resistance seen by the PV panel. For a fixed load, the equivalent resistance seen by the panel can be adjusted by changing the power converter duty cycle [5].

The literature is rich with various MPPT techniques based on different topologies and with varying complexity, cost, and overall produced efficiency. The Hill Climbing (HC) and the Perturb and Observe (P&O) are the most known and commercially used techniques [6], [8]. Other modified methods such as the incremental Conductance (INC) technique, the neural network (NN) technique, and fuzzy logic controller technique, have been also reported to improve the performance of these techniques. In HC-MPPT technique, the duty cycle is directly incremented or decremented in fixed steps depending on the panel voltage and power values until the maximum power point (MPP) is reached. The P&O technique shares the same HC concept of operation, but with an additional PI control loop. In the P&O, the converter input reference voltage is the perturbed variable and the duty cycle is computed through an additional PI control loop. The additional control loop results in an increase in the P&O efficiency, as the system demonstrates a faster dynamic performance and better-regulated PV output voltage compared to HC.

The P&O method is commonly used because of its simplicity and ease of implementation [6], [7].

Furthermore, P&O (with a small step size) in nominal conditions can have MPPT efficiencies mostly the same like other complex techniques, and still easier implementation [7]. However, the drawback of this technique is that the operating point of the PV array oscillates around the MPP. Therefore, the power loss may increase. Furthermore, when the solar radiation changes rapidly, the P&O method probably fails to track the MPP. Another possible disadvantage is that the MPPT may not be able to locate the MPP as the amount of sunlight decreases, because the PV curve flattens out [6]. Recently intelligent based control schemes MPPT have been introduced.

In this paper, an intelligent control technique using fuzzy logic control is associated to an MPPT controller in order to improve energy conversion efficiency.

Fuzzy logic controller (FLC) is one of the most widely used applications of fuzzy set theory. It can be used instead of digital control systems using fuzzy sets. We can compute with words rather than numbers. Fuzzy sets are described by membership functions which are the main toll for the fuzzy operations. The implementation of linguistic fuzzy rules by human operators is desired for a complex and nonlinear systems without the requirements of mathematical models parameter estimation. In this paper, general FLC algorithm oriented on MATLAB/Simulink is presented. For the model system, five membership functions and a rule table are described. Mathematical model of the boost converter is also given. The proposed converter system is simulated by using Matlab/Simulink simple operational blocks. This simulation can generate two different solutions for the control of converter system; one is P&O controller [10] and the other one is FLC controller.

The circuit diagram of the energy conversion system is shown in figure 1. The system consists of photovoltaic panel, a DC-DC boost converter, a control unit and a resistive load. The first stage of the system is solar panel. The I-V characteristic of a panel depends on the temperature and solar irradiance. The three most important characteristics of PV panel are the short circuit current, open circuit voltage and the MPP that is are function of temperature and irradiance. The power stage is the well known Boost converter witch its duty cycle is continuously adjusted to track the maximum power point that can be delivered by the PV panel at a given irradiance and temperature. The MPP tracker, which is based on fuzzy logic control, has the objective to draw as much power as possible from the PV module by adjusting continuously the duty cycle of the DC-DC converter. This point corresponds to the maximum power point (MPP) on the PV curve.

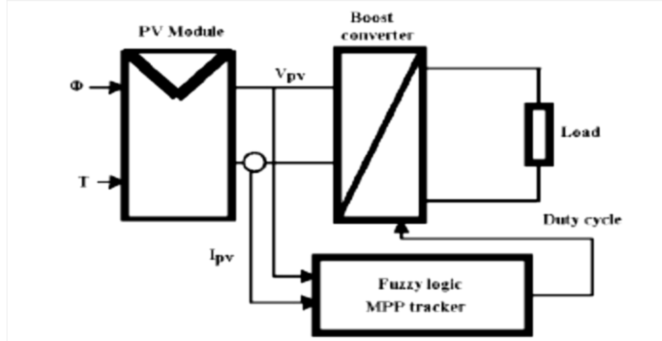

Fig. 1 Schematic diagram of the proposed power conversion PV array.

2. PV array

Photovoltaic cell is the most basic generation part in PV system. Single-diode mathematic model is applicable to simulate silicon photovoltaic cells, which consists of a photocurrent source I_{ph}, a nonlinear diode, internal resistances R_s and R_{sh}, as shown in figure 2.

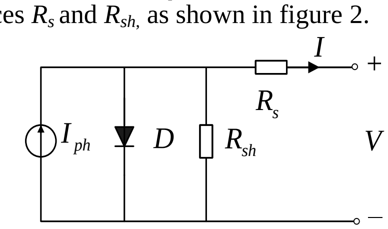

Fig. 2 Single-diode mathematic model of a PV cell.

The mathematic relationship for the current and voltage in the single-diode equivalent circuit can be described as:

$$I = I_{ph} - I_s(e^{\frac{q(V+IR_s)}{AkT}} - 1) - \frac{V + IR_s}{R_{sh}} \quad (1)$$

where, I_{ph} is photocurrent; I_s is diode saturation current; q is coulomb constant (1.602e^{-19}C); k is Boltzman's constant (1.381e-23 J/K); T is cell temperature (K); A is P-N junction ideality factor; R_s and R_{sh} are intrinsic series resistances.

Photocurrent is the function of solar radiation and cell temperature described as:

$$I_{ph} = \left(\frac{S}{S_{ref}}\right)\left[I_{ph,ref} + C_T(T - T_{ref})\right] \quad (2)$$

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where, S is the real solar radiation (W/m^2); S_{ref} , T_{ref} , $I_{ph,ref}$ is the solar radiation, cell absolute temperature, photocurrent in standard test conditions respectively; C_T is the temperature coefficient (A/K).
Diode saturation current varies with the cell temperature

$$I_s = I_{s,ref}\left(\frac{T}{T_{ref}}\right)^3 e^{\left[\frac{qE_g}{Ak}\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)\right]} \quad (3)$$

where, $I_{s,ref}$ is the diode saturation current in standard test conditions ; E_g is the band-gap energy of the cell semiconductor (eV), depending on the cell material.
When PV cells are arranged together in series and parallel to form arrays these cells are usually considered to have the same characteristics. The equivalent circuit of PV array can be described as figure 3.

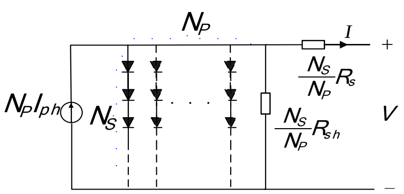


Fig. 3 Single-diode mathematic model of a PV array.

The relationship of the voltage and current in PV array is

$$I = N_P I_{ph} - N_P I_S \left(e^{\frac{q}{AkT}\left(\frac{V}{N_S}+\frac{IR_S}{N_P}\right)} - 1\right) - \frac{N_P}{R_{sh}}\left(\frac{V}{N_S}+\frac{IR_s}{N_P}\right) \quad (4)$$

where, N_S and N_P are cell numbers of the series and parallel cells respectively.
We have used Matlab/Simulink to implement the model of the solar PV panel shown in figure 4.

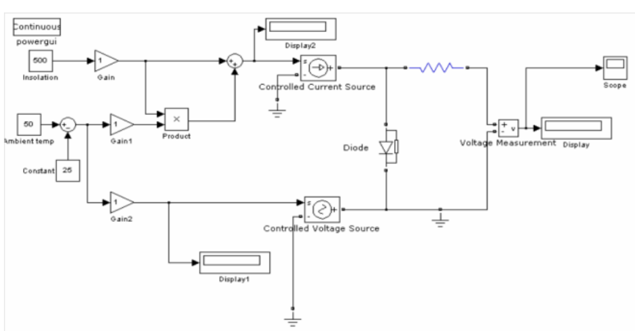


Fig. 4 Simulink model of the solar PV module.

With different temperatures and solar radiations, the output characteristics of PV array are simulated as fig.5 and fig. 6.

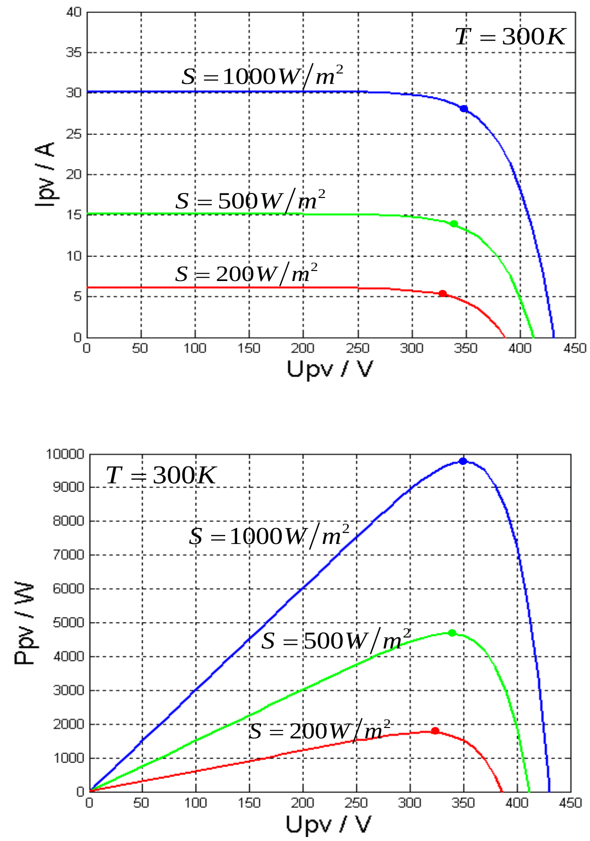
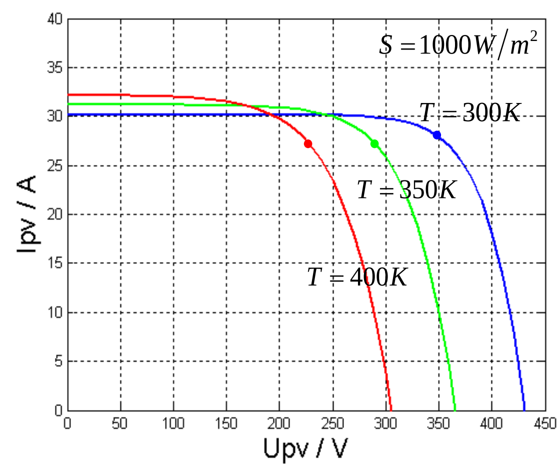


Fig. 5 Characteristic curves with different solar irradiations.



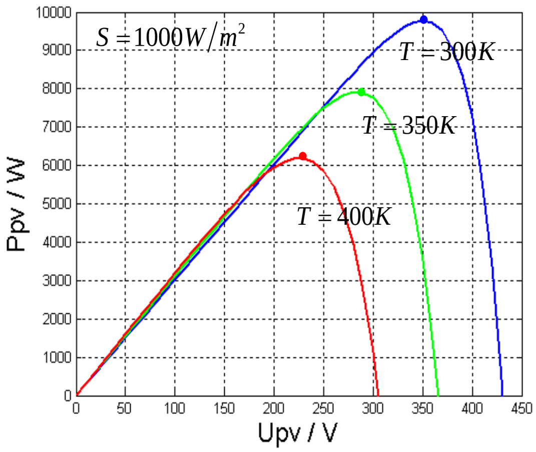


Fig. 6 Characteristic curves with different cell temperatures.

As shown in figure 5 and 6, PV array has nonlinear voltage-current characteristics, and there is only one unique operating point for a PV generation system with a maximum output power under a particular environmental condition.

3. Maximum Power Point Tracking

A dynamic tracking method is necessary to extract the maximum power from the PV cells [4]. Many researches has been developed concerning the different algorithms for the maximum power point tracking (MPPT) considering the variations of the system parameters and/or weather changes [3], [7], such as perturb and observe method, open and short circuit method, incremental conductance algorithm, fussy logic and artificial neural network. The block diagram in Fig.2 presents a PV generator with MPPT [6], [12]. The load or the battery can be charged from a PV panel using a MPPT circuit with a specific controller to track the peak power generated by the PV panel.
Other protection devices can be added. The control circuit takes voltage and current feedback from the battery, and generates the duty cycle D, This last defines the output voltage of the Boost converter [13].
Many MPTT control techniques have been conceived for this purpose these last decades [2], [11]. They can be classified as:
- Voltage feedback based methods which compare the PV operating voltage with a reference voltage in order to generate the PWM control signal of the DC-DC converter [9], - Current feedback based methods which use the PV module short circuit current as a feedback in order to estimate the optimal current corresponding to the maximum power.
- Power based methods which utilize iterative algorithms to track continuously the MPP through the current and voltage measurement of the PV module. In this category, one of the most successful and used method is perturbation and observation (P&O).

4. DC/DC Converter modeling

In Figure 7 it is shown the electrical circuit of a boost converter. The power switch is responsible to modulate the energy transfer from the input source to the load by varying the duty cycle D [7]. The classical relationship between input and output voltages of a boost converter operating at steady state condition is given by:

$$\frac{V_0}{V_i} = \frac{1}{1 - D} \quad (5)$$

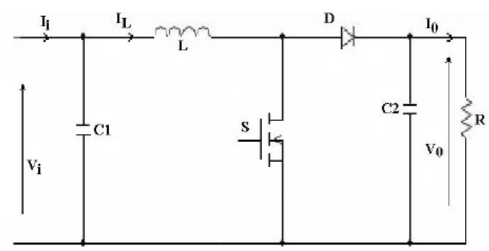


Fig. 7 Boost converter circuit.

The control strategy lies in the manipulation of the duty cycle of the switch which causes the voltage change.
When the switch is closed and the inductor is charged by the source through the switch. The charging current is exponential in nature but for simplicity is assumed to be linearly varying. The diode restricts the flow of current from the source to the load and the demand of the load is met by the discharging of the capacitor. When the switch is open and the diode is forward biased. The inductor now discharges and together with the source charges the capacitor and meets the load demands. The load current variation is very small and in many cases it is assumed constant throughout the operation.
We have used the software MATLAB/Simulink to implement the model of PV system.

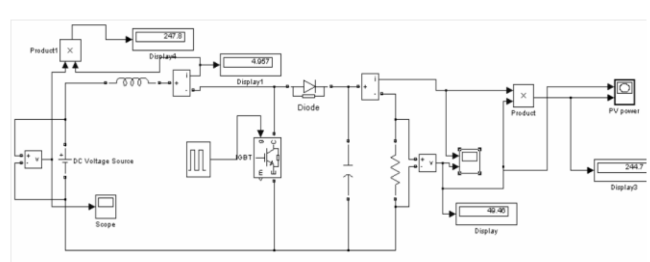


Fig. 8 Simulink model of the boost converter.

5. The new MPPT strategy

As is well known, the maximum power point (MPP) of photovoltaic power generation system depends on array temperature and solar irradiation, so it is necessary to constantly track MPP of solar array. For years, research has focused on various MPP control algorithms to draw the maximum power of the solar array. In this section, the effectiveness of these two different control algorithm are thoroughly investigated via numerical simulation.

5.1 P&O controller method

The P&O algorithm is most commonly used in PV systems applications due to its ease of implementation and simplicity. It is an iterative method for obtaining MPP. Whereas, it measures a PV module current and voltage, then perturbs the operating point of a PV module to encounter the change direction. Figure 9 shows the flow chart of the classical P&O algorithm.

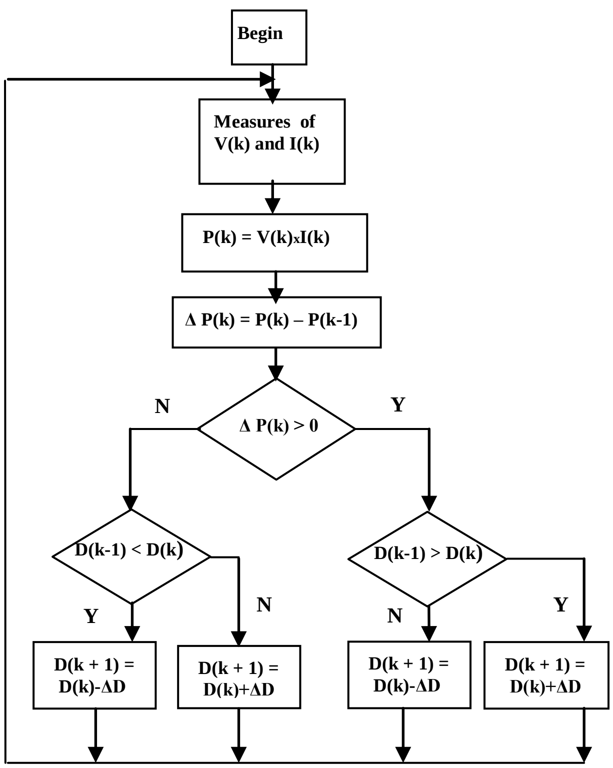


Fig. 9 Flow chart of the classical P&O algorithm.

The Perturb & Observe algorithm has been broadly used because of its practical implementation, the MPP tracker operates by periodically incrementing or decrementing the solar panel voltage, current or the duty cycle comparing to the PV output power with that of the previous perturbation cycle ,if a given perturbation leads to increase (or decrease) the output power of the PV, the successive perturbation is generated in the same (or opposite) direction, on figure 9 , we consider that the maximum power point (MPP) is Xm, if the operating point Xi is on the left of MPP , we must decrease the duty cycle until MPP, if the operating point is on the right of the MPP , we augment the duty cycle to MPP [9].

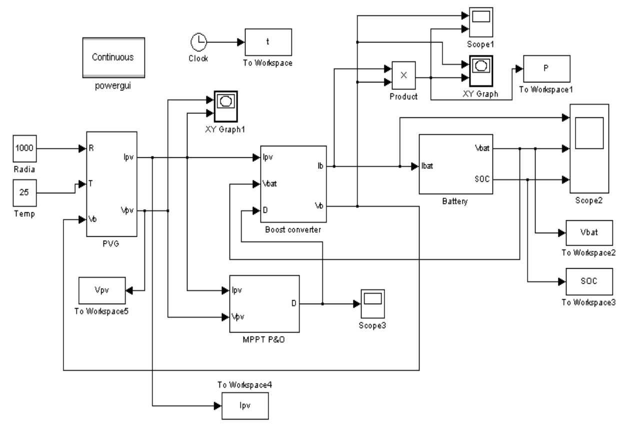


Fig. 10 Simulink model for P&O Algorithm.

Results of simulation for different tests obtained with the P&O algorithm [10].are presented and compared to those obtained with the fuzzy logic MPPT controller in section 6.

5.2 Fuzzy logic controller method

This method uses fuzzy logic to have a faster controller response and to increase system stability once reached the MPP [1]. The tracking of the MPP will be divided into two phases: the first phase is of tough research, with a significant step to improve the response of the MPPT controller, the second one is the fine phase where the step is very small, thus ensuring the system stability and decrease the maximum oscillations around the MPP. This feature of the fuzzy controller demonstrates its effectiveness and makes it among the best MPP tracking devices [9]. The fuzzy controller consists of three blocks: the fuzzification of input variables which is performed in the first block, it allows the passage from the real domain to fuzzy domain. The second block is devoted to inference rules, while the last block is the defuzzification for returning to the real domain. This last operation uses the center of mass to determine the value of the output. Figure 11 shows the basic structure of the used MPPT Fuzzy controller [9]. The fuzzy logic controller consists of four functional blocks: fuzzification, fuzzy rules, an inference engine and the defuzzification. E and CE are the inputs scaling factors, and D denotes the output of the fuzzy process.

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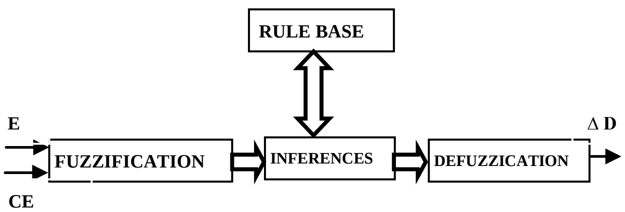

Fig. 11 Block Diagram of the Fuzzy Logic Controller.

Recently fuzzy logic controllers have been introduced in the tracking of the MPP in PV systems [12], [13]. They have the advantage to be robust and relatively simple to design as they do not require the knowledge of the exact model. They do require in the other hand the complete knowledge of the operation of the PV system by the designer. The proposed FL MPPT Controller, shown in figure 12, has two inputs and one output. The two inputs of the FLC are the error *E* and the associated change of error *CE*.

Where P(k) and V(k) refers to the output power and voltage of the PV panel at the sampling instant k. The two fuzzy controllers E and CE are normalized with a gain (gE and gCE), the output is denormalized with a gain g.Δd.

$$\Delta D('k) = g.\Delta d \quad (9)$$

Fuzzification:

The fuzzy process requires that each variable used in describing the control rules has to be expressed in terms of fuzzy set notations with linguistic labels [1, 2, 3]. Figure 13 show the memberships functions of the input variables E(k) and CE(k) and the output variable ΔD(k). In which each membership function is assigned with five fuzzy set, including PB (Positive Big), PS (Positive Small), ZE (Zero Equivalent), NS (Negative Small) and NB (Negative Big).

Fuzzy rules and inference engine:

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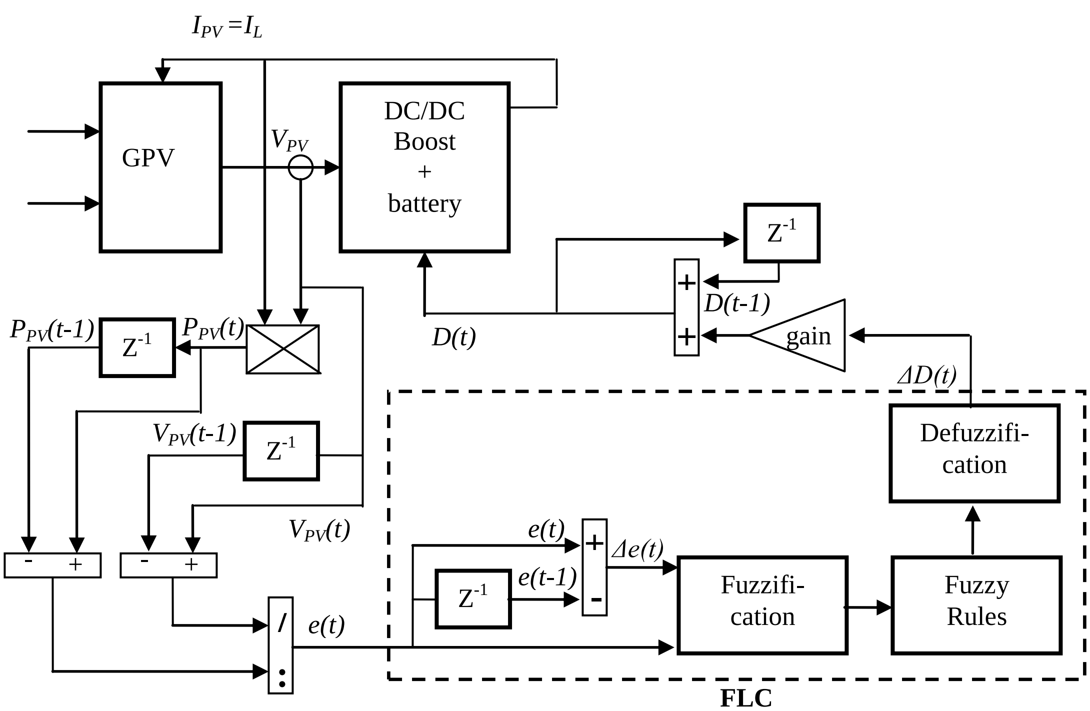


Fig. 12 Fuzzy Logic Controller.

The error is given by:

$$E(k) = \partial P/\partial V = [P(k)-P(k-1)]/[V(k)-V(k-1)] \quad (6)$$

And the error change is:

$$CE(k) = E(k) - E(k-1) \quad (7)$$

And the output of the controller (the duty cycle D) is given by:

$$D(k) = D(k-1) + \Delta D(k) \quad (8)$$

The kernel of fuzzy logic controller is the fuzzy inference system. Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made. The proposed Mamdani-type inference system is dedicated to force the error function to zero. Two cases are considered [13]:

• **First case:** *E* is positive; working point is on the left of the MPP. If the change of error *CE* is positive, then the working point converges toward the MPP. If *CE* is negative, the inverse that occurs.

• **Second case**: *E* is negative; the operation point is, therefore, on the right of the MPP. In this case if *CE* is positive, the operation point moves away of the MPP and vice versa if *CE* is negative.

From that, we summarises, in table1, this process reasoning as a set of a fuzzy IF-THEN rules [12].

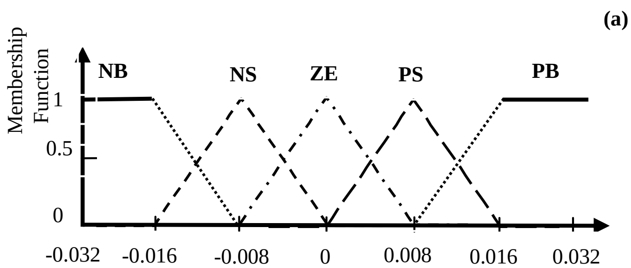
Defuzzification:

The process of Defuzzification calculates the crisp output of the FLC. It describes the mapping from a space of fuzzy logic statement, corresponding to the inferred output, into a non-fuzzy control action. In this paper the centre of gravity Defuzzifier, which is the most common one, is adopted.

The control rules are indicated in Table I with E and CE as inputs and D as the output.

Table 1: Fuzzy rule table

E↓ \ E→	NB	NS	ZE	PS	PB
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	ZE	NS
PS	NS	NS	NS	ZE	ZE
PB	NB	NB	NB	ZE	ZE



These two variables and the control action D for the tracking of the maximum power point are illustrated in fig. 13.

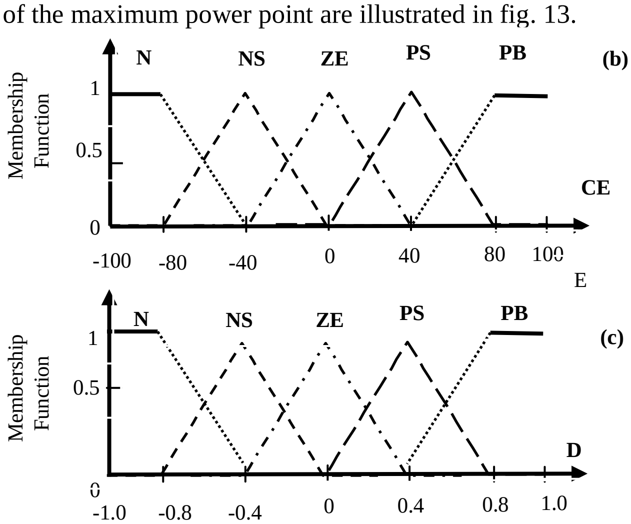


Fig. 13 Membership functions of (a) The error E, (b) The error variation CE and (c) The duty cycle D.

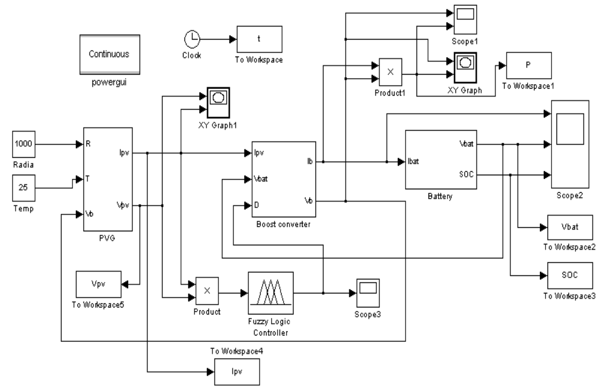


Fig. 14 Global Simulink Model for the fuzzy MPPT controller.

6. Simulations results

6.1 Operation in standard environmental conditions

The figures 15, 16 and 17 below allow us to visualize the output PV panel current, voltage and power using the fuzzy controllers in standard atmospheric conditions (1000W/m2, 25°C).

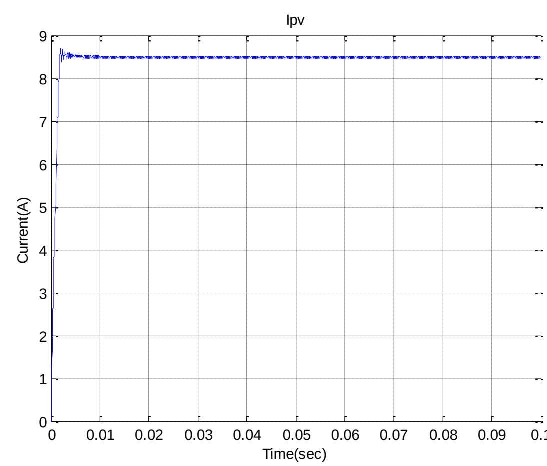


Fig. 15 The output PV panel current.

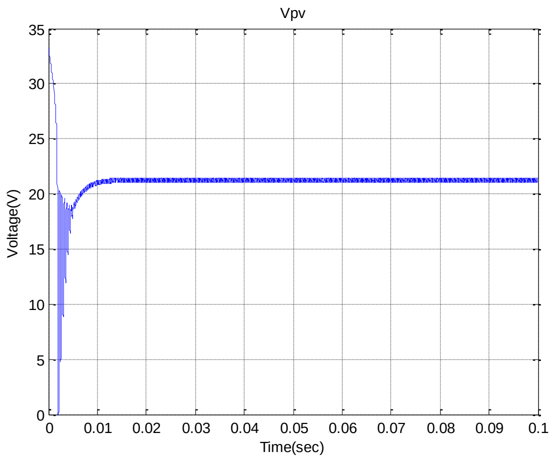


Fig. 16 The output PV panel voltage.

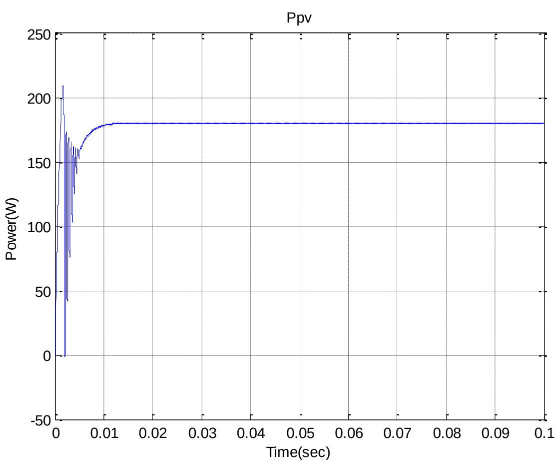


Fig. 17 The output PV panel power.

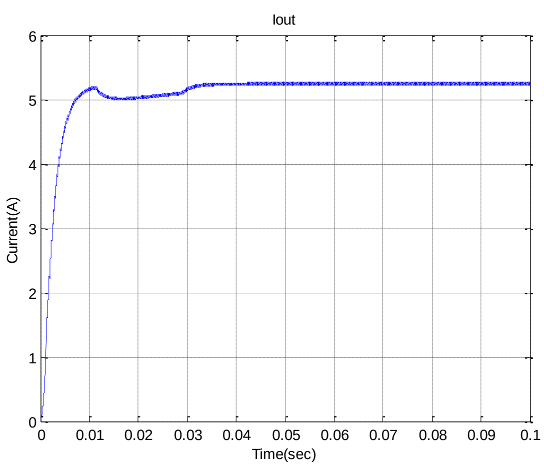


Fig. 18 The Boost converter output current with P&O controller.

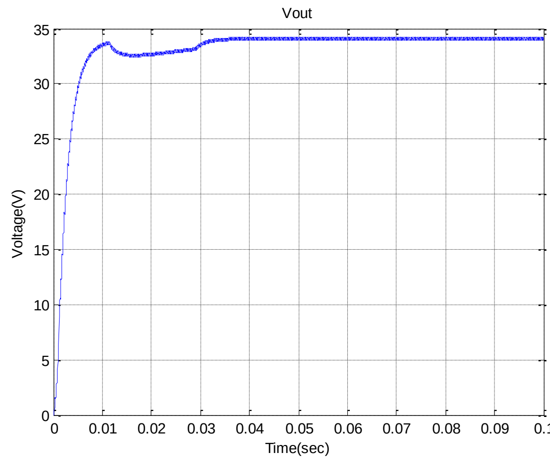


Fig. 19 The Boost converter output voltage with P&O controller.

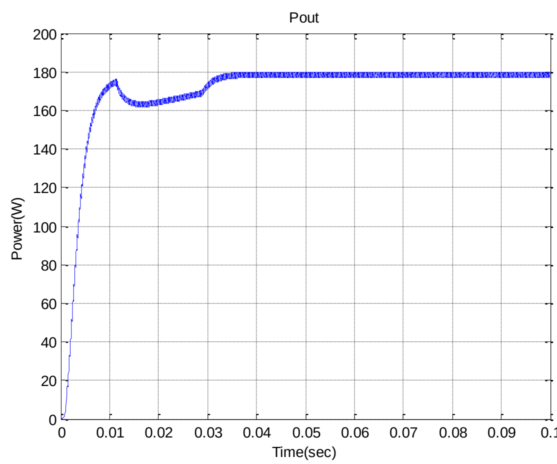


Fig. 20 The Boost converter output current with P&O controller

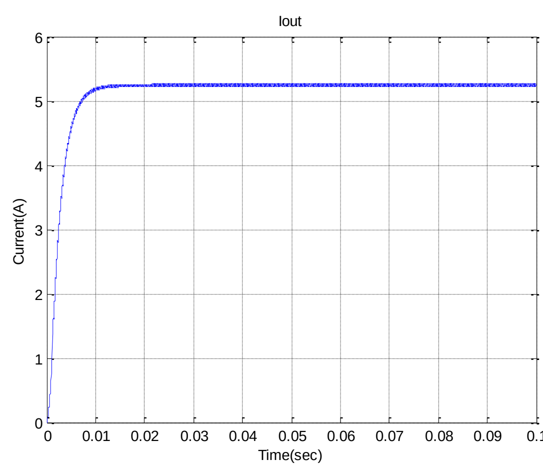


Fig. 21 The Boost converter output current with Fuzzy logic controller.

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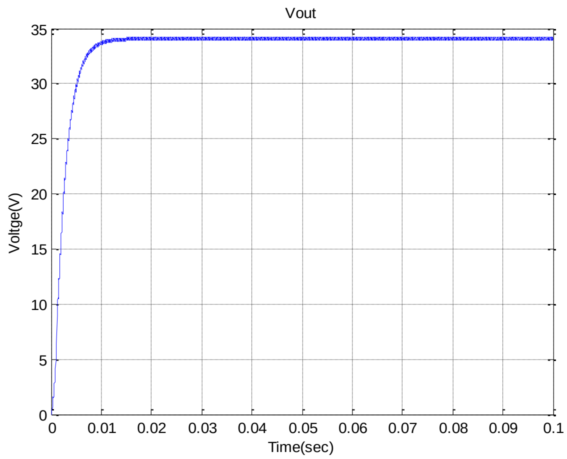

Fig. 22 The Boost converter output voltage with the Fuzzy logic controller.

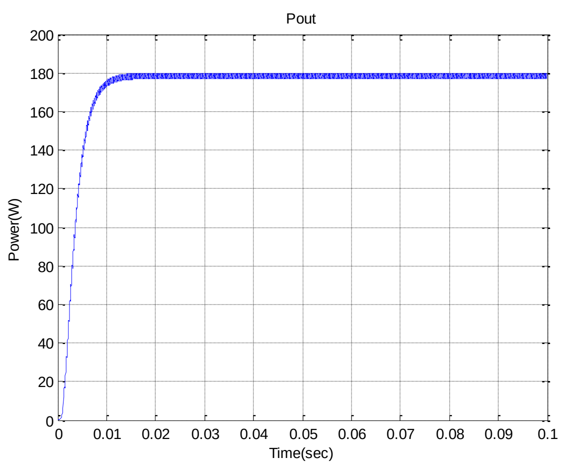

Fig. 23 The Boost converter output power with Fuzzy logic controller.

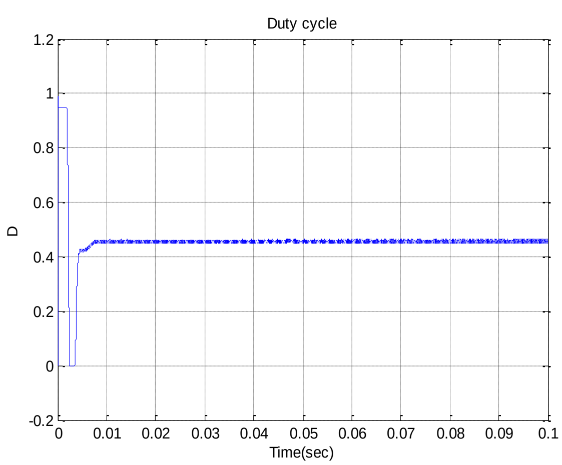

Fig. 24 Duty cycle.

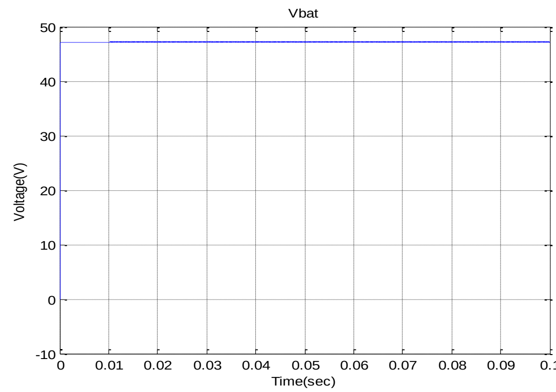

Fig. 25 The output voltage of battery with Fuzzy logic controller.

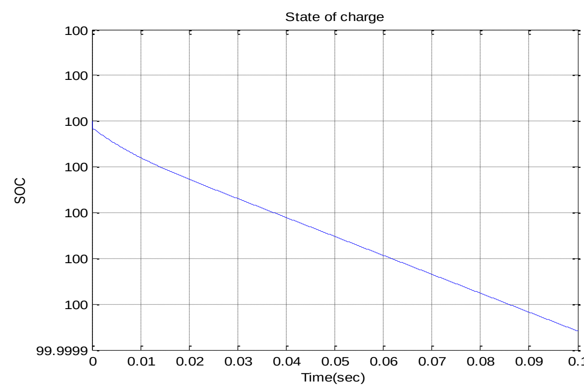

Fig. 26 The state of charge of battery with Fuzzy logic controller.

6.2 Operation in variable solar radiation conditions

To visualize the behavior of our system in real conditions, we vary the irradiation as the increment step. These variations allow us to study the robustness of our system using fuzzy logic controller.

We have tested the response of the two controllers, for a variation in solar radiation from1000 W/m2 to 600 W/m2 in order to assess the very good performance of the fuzzy MPPT controller over other types classical P&O and fuzzy controllers.

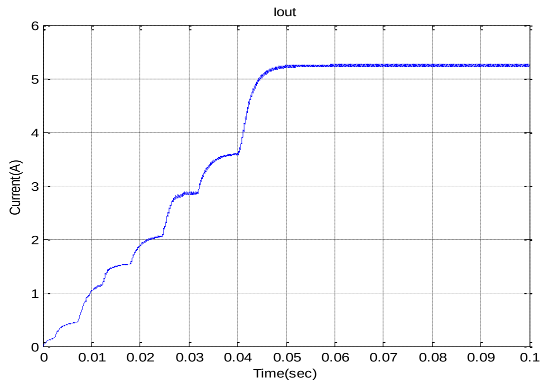

Fig. 27 The Boost converter output current with a step change of irradiance with fuzzy logic controller.

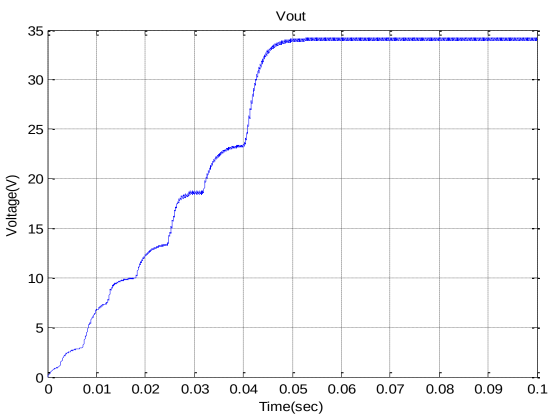

Fig. 28 The Boost converter output voltage with a step change of irradiance with fuzzy logic controller.

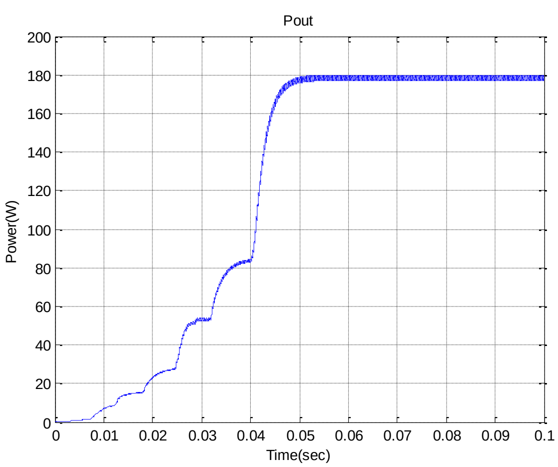

Fig. 29 The Boost converter output Power with a step change of irradiance with fuzzy logic controller.

The simulation results illustrated in figures 27, 28 and 29 confirm that the fuzzy controller has good performance response such as rapidity, the time response is about 30ms, and damping of the overshoot when the solar radiation decreases rapidly due to shading for example eclipses, considering that the PV temperature is kept constant at 25°C throughout the simulation time interval.

7. Conclusions

We have considered in our present research work the simulation of two methods of control: perturb and observe (P&O) and fuzzy controllers. Both of them were applied on a chain of energy conversion supplied by DC-DC boost converter. We compared the obtained simulation results, by subjecting the controlled system to the same environmental conditions. The simulations have shown that the use of fuzzy logic controller can improve the efficiency of the overall system by minimizing the energy losses when the change of irradiation is frequent rather than the classical method such as perturb and observe technique.

We conclude that the MPPT fuzzy controller which is based on the experience of the operator has a very good performance. It reduces the time responses of the photovoltaic system to perturbations and insures the continuity of the operation at the time in response to the continued maximum power point and it also eliminates the fluctuations around this point. This quality shows the effectiveness of the proposed fuzzy controller for photovoltaic systems as well in standard as in variable environmental conditions. The results obtained for this energy conversion system, show that by using the MPPT fuzzy controller, there is a compromise between rapidity in transient regime and stability in steady state. These used controllers results can be compared to other methods of control such as the use of neural networks controllers to optimize the PV boost converter. This could be one of the ideas of our future work in this research area.

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Mohamed Tahar Makhloufi was born on February 06, 1961. He received the B.Sc. and M.Sc. degrees in Electronics from the University of Batna, Algeria, in 1987 and 2000, respectively.
He is now teaching as a lecturer in Power Electronics and Control at the Department of Electronics, Faculty of Engineering, University of Batna. He has been a member of staff of Laboratory of Advanced Electronics (LEA) from 2002. He is a member of many research projects if Power electronics and control such as the applications of solar energy in autonomous vehicles and residential power supplies in remote areas. He has published three international papers in photovoltaic energy conversion and control using modern control techniques.
His research interests include power resonant converters control using artificial intelligence strategies and their applications in various technical devices such as robots and artificial satellites.

Mohamed Salah Khireddine was born at Tolga (Algeria) in 1956. He obtained the Informatics Engineer Degree from the University of Algiers in 1980. He received his Doctorate (PhD) in Automation and computer science from the University of Aix-Marseille (France) in July 1990. In 2010 he received a postdoctoral degree in "Habilitation of conducting research in Control Engineering" from the Batna University where he is currently Associate professor in Automation and Industrial Computing and research member in the Advanced Electronice Laboratory (LEA) and head of artificial intelligence team in Productics Research Laboratory (LRP). He is currently supervising many doctors' and master's thesis in different areas of power electronics and robotics. He has published ten papers in the real-time control of mobile robots, fault diagnosis and fault tolerant control of robot arms, and solar photovoltaic energy control.
His research interests include Faults Diagnosis, Fault Tolerant Control, Artificial Intelligence, Control Systems and Robotics.

Abdessemed Yassine was born on January, 28th 1959 at Batna, Algeria. He carried out under-graduated studies at the University of Constantine, Algeria from 1978 till 1980 and has obtained the degree of bachelor of engineering from the university of Algiers-ENPA-Algiers, Algeria in June 1983. From 1985 till 1990 he carried out post- graduated and research studies in power electronics and real-time control of AC electrical drives.
He was awarded the PhD degree from the department of electrical engineering of the University of Bristol, Great-Britain, in January 1991. He has been associate lecturer during five years at the electrical department, Faculty of Engineering of Bristol. He is now an associate professor in applied electronics, power electronics and control at the Department of Electronics of Batna. He has supervised many final year graduate projects and master by research thesis in electrical engineering and applied electronics, control and robotics. He is currently supervising many doctors' and master's thesis in different areas of power electronics and robotics. He has published five papers in the real-time control of mobile robots, data fusion for the mobile robots localization, fault diagnosis and tolerant control of tele-operated robot arms, and solar photovoltaic energy control. His current main research work areas are power electronics, the neuro-fuzzy logic applied to the control of mobile robots and robot arms, and vision control of robot arms.

Abdelhalim Boutarfa was born in Lyon (France) in 1958. He has graduated from University of Constantine (Algeria) in Physics in 1982. He obtained the Electronic Engineer Degree from the Polytechnic School of Algiers in 1987, a Magister (Master) in 2002 and a Doctorate (PhD) in 2006 in "Control Engineering" at the University of Batna.
In 2007 he received a postdoctoral degree in "Habilitation of conducting research in Control Engineering" from the same University where he is currently full professor and research member in the Advanced Electronice Laboratory (LEA). He is also, since October 2010 the Project Manager of the National Center for Technology Transfer at the University of Setif (Algeria).
His research interest includes applications of neural networks to pattern recognition, robotic vision, and industrial processes. He focuses his research on pattern recognition, learning, analysis and intelligent control of large scale complex systems.