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Simulation and Real Implementation of the Fuzzy MPPT Algorithm for Photovoltaic Panel

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Abstract

Objectives: The objective of this study deals with the optimization of extracting the ultimate power from a PV panel by means of the fuzzy-MPPT algorithm. **Methods/Statistical Analysis:** The methodological framework, in this paper, is based on a fuzzy logic controller which tracks the maximum power from a boost-based PV system. This approach is used to enhance its dynamic response under varying irradiations and temperature conditions. Numerical simulations and practical experiments results are carried out to highlight the tracking control performance and the advantages of the fuzzy-MPPT compared to a P&O as one of the most widely conventional methods. The fuzzy logic strategy provides better and reliable control for this application under different variations on climatic conditions. **Findings:** The findings achieved are experimental tests showed that for the same weather conditions; the produced PV power by the P&O-MPPT algorithm is 14% less than the power produced when the fuzzy algorithm is used.

Keywords: DC-DC Boost Converter, dSPACE1104, Fuzzy Logic Controller (FLC), Maximum Power Point Tracking (MPPT), MATLAB/Simulink, Photovoltaic (PV)

1. Introduction

The scarcity of energy resources and environmental issues associated to it like increasing environmental pollution and global warming has sparked interest in the renewable energy. As one form of renewable energy, Photovoltaic solar energy can help overcome these problems. A great attention has been drawn towards solar photovoltaic systems in research. The application of solar power ranges from residential, vehicular, and commercial to military purposes.

Furthermore, more research work has been focused on maximizing the energy produced by the PV systems through improving MPPT structures such way to boost the effectiveness of the solar photovoltaic systems.

Environmental conditions, namely changes in cell temperature, sunlight incident angle, solar irradiation, and load condition act on the production of the solar power by the photovoltaic cells. The maximum power point tracking is a prominent element in the control design for PV production. The nonlinearity nature of the I-V characteristic of the solar cell as long as the unpredictable variations of the environmental conditions deal with MPPT as a nonlinear control problem. Therefore, MPPT algorithms are crucial to maintain operation of the PV array at its MPP[1]. A huge number of MPPT

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algorithms have the necessity to amplify the production of energy mainly the incremental conductance method as well as the perturb and observe method, which, are the most accepted in usage[2]. In both techniques, the duty cycle command requires dynamic step size to ameliorate the transient response of the system[3].

It's therefore needed to introduce some artificial intelligence based techniques for instance (fuzzy logic, neural network)[4–6], sliding mode[7]and genetic algorithms[8,9], to demonstrate their high efficiency on terms of stability and response time. Fuzzy logic has the advantage of being a robust and fast controller which is implemented in order to reach the peak power point. In fact, the slope of the Power-Versus-Voltage (P-V) curve of the PV cell characteristics curves and change of this slope are the most widely adopted input variables for the MPPT algorithms, the output is a duty cycle or its variation[10–12].

Some of the previous studies have either selected P-V slope and variation of power Δ (Ppv), or the variations of power and voltage (Δ (Ppv) and Δ (Vpv)) as the input variables. While in other studies, the variations of power and current (Δ (Ppv) and Δ (Ipv)) are adopted instead[16]. Another investigation has selected the incremental conductance method used conductance and increment of conductance as the fuzzy input variables for MPP evaluation[17]. In a reported fuzzy MPPT algorithm, the sum of the arctangent of the conductance and arctangent of the conductance increment are considered as the input variables[18].

In this study, the new technique, which based on fuzzy logic, is presented. In order to improve its dynamic response under different operating conditions and assure fast convergence to MPP, this technique is inducted in the proposed MPPT. S (k), Δ S (k), Vpv and variation of duty cycle Δ U (k) are the inputs parameters of the proposed controller. These parameters used to determine the most important increment which is added to the operating voltage in order to get a fast pursuing of the MPP. The performance indicators which characterized the proposed strategy are assessed by MATLAB/Simulink. It is then experimentally implemented under varying meteoric conditions like variation in solar irradiance. dSPACE carte real time control is used for the implementation of the MPPT hardware setup. Data acquisition and the control system are implemented by using the dSPACE 1104 software.

Section 2 in this paper presents the stand-alone photovoltaic system which consists of a photovoltaic panel connected to a boost converter for providing solar energy to a resistive load. To track the MPP of the PV system, an MPPT method based on a fuzzy logic is dealt with in Section 3. The obtained simulation results using the MATLAB/Simulink are given to evaluate the performance of the optimized fuzzy controller in terms of speed and accuracy, while in Section 4, an experimental implementation of the MPPT algorithm is presented where data acquisition and the control of the proposed fuzzy MPPT method are achieved by dSPACE 1104.The final section concludes the work.

2. Photovoltaic System

Before proceeding to develop our control, we present the modeling of different components of PV system.

2.1 PV model and these Characteristics

The efficiency of PV modules relies on the material used in solar cells and how well cells are arranged to form a module. The effectiveness can drop further due to other factors see PV module temperature and load conditions. In fact, for further understanding the analysis, a resistive load was considered in this study.

In general, when a PV module is directly connected to a load, the operating point is seldom the MPP. Consequently, a power conversion system was needed to adjust the energy flow from the PV array to the charge. The evolution of the generated power curves as a function of voltage are shown in Figures 1 and 2, respectively, for a given constant irradiation and different values of temperature and then for a given constant temperature and different values of irradiation. In fact, the operating point can be adjusted by shifting the values of the resistive load.

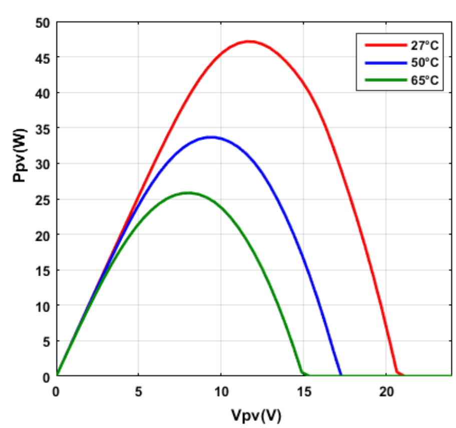

Figure 1. P-V power curves with different T (G=1000w/m²).

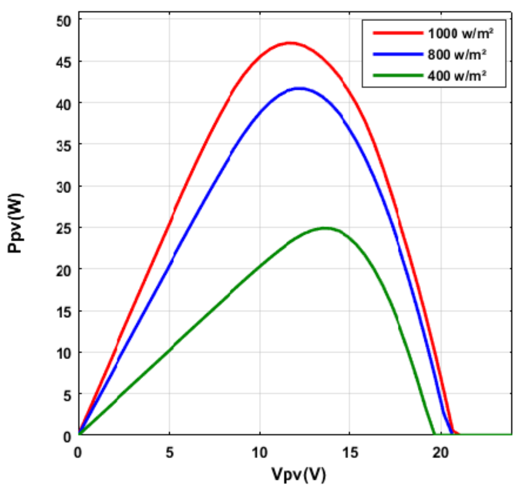

Figure 2. P-V power curves with different G (T=27°C).

For modeling a photovoltaic module, a photovoltaic cell must be initially established as depicted in Figure 3.

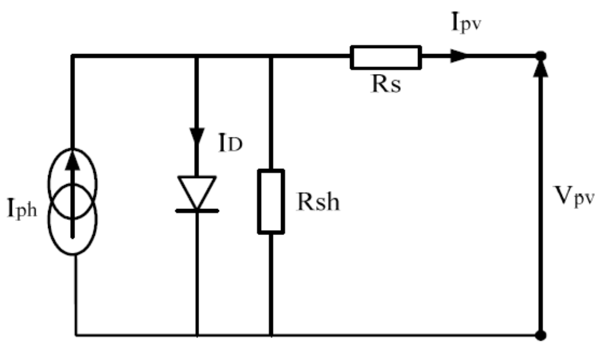

Figure 3. Equivalent circuit for PV cell.

The electrical equivalent circuit of the PV cell consists of a current generator, in parallel with a diode and connected to a serial resistor, namely Rs and a shunt resistance, namely Rsh.

The PV cell model is described by the following equations[19,20]:

$$I_{pv} = I_{ph} - I_0 \left[\exp\left(\frac{V_{pv} + R_s I_{pv}}{\eta V_t} \right) - 1 \right] - \left(\frac{V_{pv} + R_s I_{pv}}{R_{sh}} \right) \quad (1)$$

$$V_t = \frac{mKT}{q} \quad (2)$$

m is the number of cells that are electrically connected in series so as to provide the desired power and voltage, K is the Boltzmann's constant, T the absolute temperature and q the electronic charge.

The expression of the generated current which depends on solar radiation (G) and temperature (T) is given by the following equation[20,21]:

$$I_{ph} = \left[I_{sc} + K_t \left(T - T_r \right) \right] \text{—} \quad (3)$$

$$I_0 = \frac{I_{ph}}{\exp\left(\frac{qV_{oc}}{KT} \right) - 1} \quad (4)$$

G_r, T_r are respectively the reference solar radiation and temperature of the cell. V_t, K_t are respectively the thermal voltage and the coefficient temperature of the short circuit current. V_{oc} is the open circuit voltage, I_{sc} is the short circuit current,

I_{ph} represents the light current (A).

I_0 that represents the diode reverse saturation current.

2.2 DC-DC Boost Converter

The boost converter is shown in Figure 4.

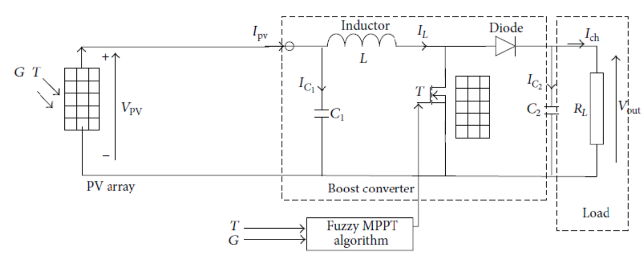

Figure 4. Structure of photovoltaic system.

The great importance that the dc converters have gained in many domains, it started from low to high-powers applications.

In this study, a boost -converter is selected to play two major tasks; it regulates the fluctuating input voltage coming from the PV panel and assumes the tracking of the maximum power point by the adjustment of the duty cycle.

The solar power generation system under study consists of a photovoltaic panel feeding into a resistive load through a boost converter. Figure 4 shows the boost-based

PV system equivalent circuit. The system's average model is given in Equation (5).

$$\begin{cases} \dfrac{dI_L}{dt} = \dfrac{R_b}{L} I_L + \dfrac{1}{L} V_{pv} - \dfrac{V_D}{L} + \dfrac{(R_b - R_m) I_L + V_D + V_B}{L} u \\ \dfrac{dV_{pv}}{dt} = -\dfrac{1}{C1} I_L + \dfrac{I_{pv}}{C1} \\ \dfrac{dV_B}{dt} = \dfrac{1}{C2} I_L - \dfrac{1}{R_L C2} V_B - \dfrac{I_L}{C2} u \end{cases} \tag{5}$$

Where V_{pv} and I_{pv} are the PV panel voltage and current. L, R_b and I_L are the self-inductance, resistance and current. R_m is a resistance characterizing IGBT losses. $C1$, $C2$, V_D and V_B are respectively the input capacitance, the output capacitance , the diode forward voltage and the load voltage, u is the control input. Considering the PV current as an exogenous input, we get the following state representation (6).

$$\begin{pmatrix} \dfrac{dI_L}{dt} \\ \dfrac{dV_{pv}}{dt} \\ \dfrac{dV_B}{dt} \end{pmatrix} = \begin{pmatrix} \dfrac{R_b}{L} \dfrac{1}{L} - \dfrac{1}{L} \\ -\dfrac{1}{C1} 0 0 \\ \dfrac{1}{C2} 0 - \dfrac{1}{R_L C2} \end{pmatrix} \begin{pmatrix} I_L \\ V_{pv} \\ V_B \end{pmatrix} + \begin{pmatrix} \dfrac{(R_b - R_m) I_L + V_D + V_B}{L} \\ 0 \\ -\dfrac{I_L}{C2} \end{pmatrix} u + \begin{pmatrix} -\dfrac{V_D}{L} \\ \dfrac{I_{pv}}{C1} \\ 0 \end{pmatrix} \tag{6}$$

Control of the boost converter switch is achieved by an MPPT controller that will assure the variation of the duty cycle of the converter in order to extract the maximum possible power from the PV array. The output voltage of the boost which is also the voltage across the load, obtained by the MPPT algorithm is described by Equation (7).

$$V_{out} = \frac{1}{1 - D} V_{in} \tag{7}$$

D is the duty cycle of the converter.

2.3. MPPT controller

The design of MPPT controllers seems an intriguing subject due to the nonlinearity of DC-DC converters and PV modules. Almost, the controller generates a reference voltage to a Pulse Width Modulation (PWM) generator, which provides the appropriate pulses[20]. In this way, we should have recourse to such important converter in order to ensure that the PV source operates at its maximum power point, as depicted in Figure 5. In fact, this maximum power point can only be reached by adjusting the derivative dP/dV toward zero[22,23].

According to defined parameters (G, T) and selected R_L, there exists only one Maximum Power Point (MPP). Generally, the power demanded by the load is more than the delivered one by the photovoltaic system[3]. To extract the maximum power from the photovoltaic panel, it's was therefore necessary to introduce an intelligent mechanism, is to be adapted to load change. However, a specific algorithm for pursuing the optimal operating point should be used thereof permits to stalk the maximum power.

Some of the MPPT controller objectives are:

- Getting to the MPP with small rising time in the transitional state of the process.
- Reducing the power losses in photovoltaic system.
- Minimizing the output power ripples in the steady state.
- Making the robustness to variation in parameters.

3. MPPT Control Strategy

In the present study, three control strategies are studied.

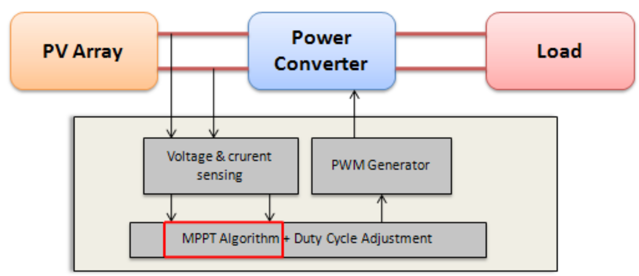

Figure 5. MPPT control strategy.

3.1 Perturb and Observe Algorithm

Indeed, it's necessary to make a comparison between the typical method of maximum power point tracking: Perturb and Observe and the proposed fuzzy MPPT strategy so that to appraise the performance of the suggested one. The main concept of this method is; the duty cycle is given periodically and the appropriate output power is compared with at the previous update, implies modifying the DC link voltage between the PV array and the power converter. The flowchart of the P&O algorithm is shown in Figure 7.

If the difference between the power values of the present and the previous states is positive, the perturbation is maintained in the same direction as described in Figure 6. If the power's difference is negative, the perturbation is reversed[24].

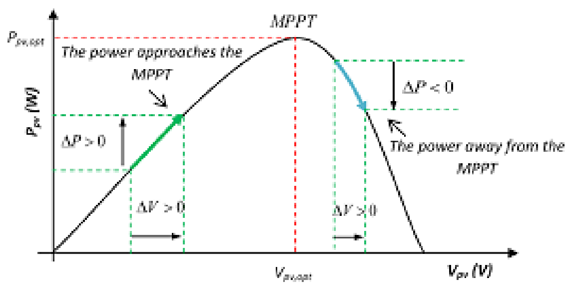

Figure 6. Power-voltage characteristic of PV panel

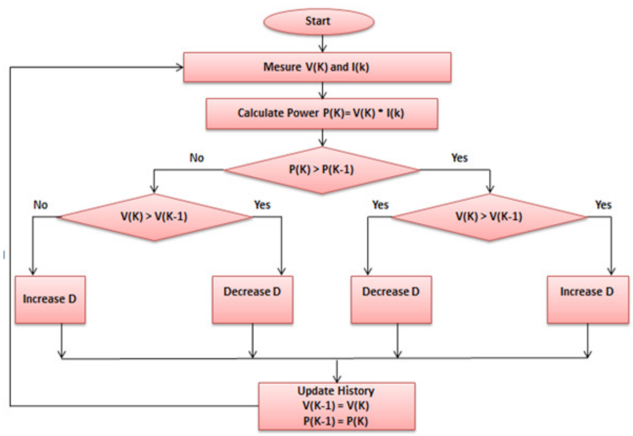

Figure 7. Flowchart of P&O algorithm.

3.2. Fuzzy MPPT Control

Fuzzy logic models are appropriate for nonlinear control especially the TS fuzzy models (Takagi-Sugeno), due to their ability to handle any nonlinear behavior and it does need mathematical equations. The performances of a TS fuzzy model rely on its complexity (Number of fuzzy rules), on the type of membership functions and also on the antecedent variables and the consequent regressors.

3.2.1 Inputs of Fuzzy Controller

This algorithm of MPPT uses the slope S (k) of the power (P-V curve), and variation of slope S (k) as the fuzzy input variables and the duty cycle as the output which controls the boost converter. These variables were defined using the following equations:

$$S(k) = \frac{\Delta P_{pv}}{\Delta V_{pv}} = \frac{P_{pv}(k) - P_{pv}(k-1)}{V_{pv}(k) - V_{pv}(k-1)} \quad (8)$$

$$\Delta S(k) = S(k) - S(k-1) \quad (9)$$

Where P_{pv} and V_{pv} are respectively the photovoltaic power and voltage of the panel. We define three fuzzy sets: Positive (P), zero (Z) and negative (N) to describe each linguistic variable.

The values of the next round of fuzzy input variables are affected by the change of the output parameter's PV panel. The controller will know then readjust the output commands accordingly. A new technique based on fuzzy logic is presented in this paper, to pursue the maximum power point of the PV array under rapidly changing weather conditions.

3.2.2 The Proposed MPPT Method based on Fuzzy Logic

A new Fuzzy logic method, of Maximum Power Point (MPPT) for photovoltaic systems is proposed, as described in Figure 8. The fuzzy controller input parameters S (k), ΔS (k), V_{pv} and variation of duty cycle ΔU (k) are used for producing the duty cycle of the converter in order to maintain the PV array's operating point at its MPP.

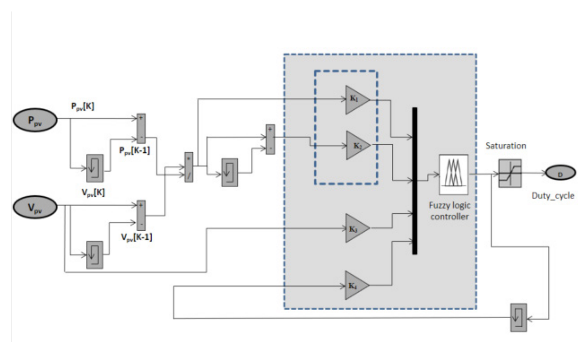

Figure 8. Structure of Fuzzy logic MPPT controller.

Where K1, K2, K3 and K4 are the scale factors (standardization), these factors are determined by trial and error method in order to have a proper transient control.

In fact, it's they which will determine the performance of the MPPT controller. The conventional MPPT algorithms consist of two inputs and one output.

In our approach, the photovoltaic voltage is added to improve the reliability and accuracy of tracking the optimal point and the variation of duty cycle is added to enhance the dynamic characteristics against change of atmospheric conditions.

The database for fuzzy rules was designed according to the fuzzy input variables, are shown in Table 1. According to fuzzy logic, define of the universe of discourse of the inputs and outputs becomes necessary because it affects directly the results.

Figure 9, 10, 11 and 12 show the corresponding input membership functions of the proposed tracker.

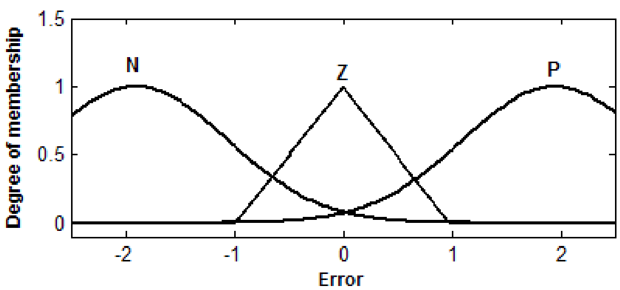

Figure 9. Membership function of error.

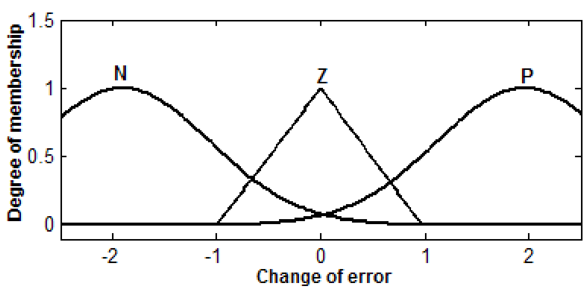

Figure 10. Membership function of change of error.

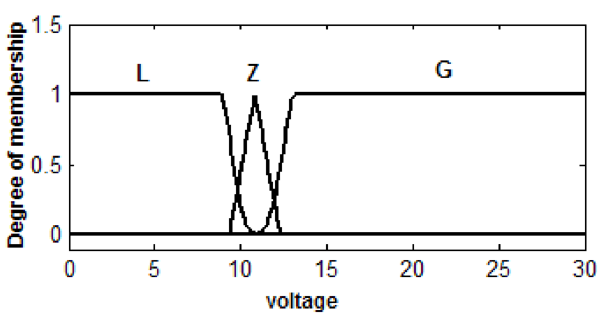

Figure 11. Membership function of voltage.

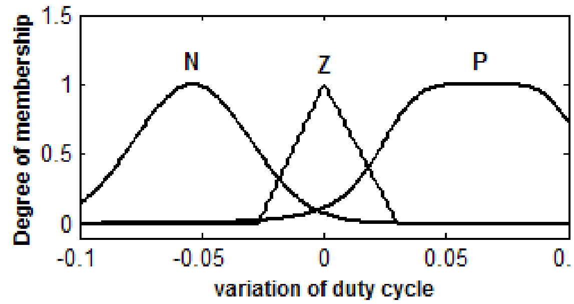

Figure 12. Membership function of variation of duty cycle.

Table 1. Rule base used in the fuzzy logic controller

Input 1	Input 2	Input 3	Input 4	Output
N	N	Z	N	mf4
N	N	G	N	mf1
N	Z	Z	Z	mf3
N	Z	G	Z	mf1
N	P	Z	P	mf5
N	P	G	P	mf4
Z	N	Z	N	mf4
Z	N	G	N	mf2
Z	Z	Z	Z	mf5
Z	P	L	P	mf8
Z	P	Z	P	mf6
Z	P	G	P	mf4
P	N	L	N	mf7
P	N	Z	N	mf5
P	Z	L	Z	mf7
P	Z	Z	Z	mf6
P	P	L	P	mf9
P	P	Z	P	mf7

3.3 Simulation Results

The proposed system is composed of photovoltaic panel of 62W, a DC/DC boost converter and resistive load. Various simulations were realized to assess the system's performances. The different parts of the study system are modeled by separate blocks, while the MPPT is controlled by conventional method P&O and the proposed Fuzzy Logic Controller (FLC). To test their performances, these techniques are tested under various weather conditions.

- Performances of the MPP Tracker Under Dynamic Climatic Conditions:

To demonstrate the performance of the proposed MPPT control approach, we apply a sudden variation of irradiation as shown in Figure 13.

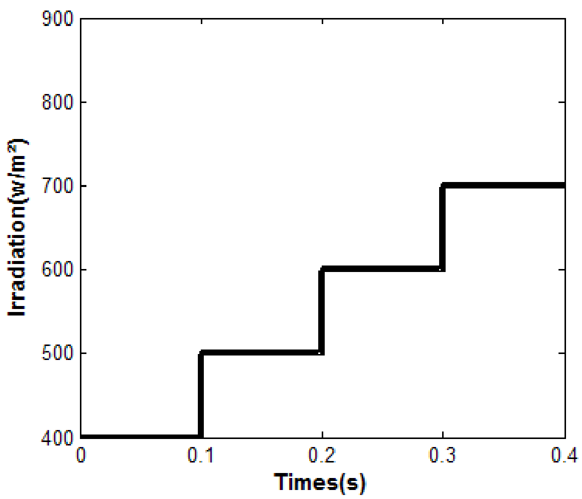

Figure 13. Evolution of irradiation.

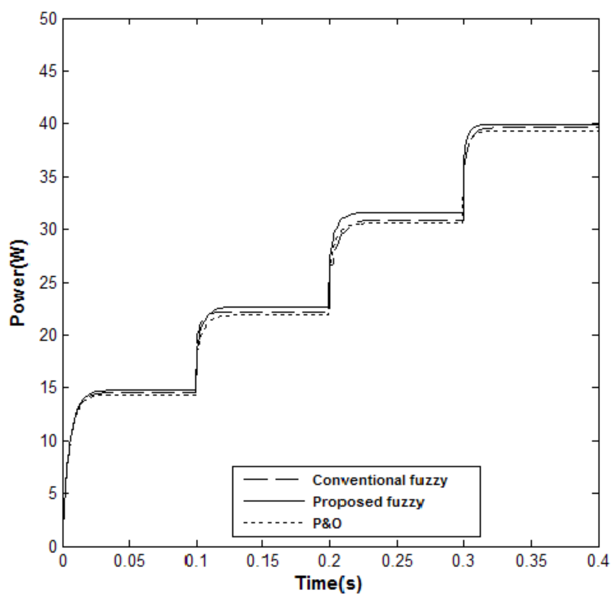

Figure 14. Comparison of three method of MPP tracking (P&O, Conventional Fuzzy logic and Proposed Fuzzy method).

We know that for each pair of irradiation and temperature there exist only one optimal operating which can be determined from the power-voltage characteristic of the PV array panel.

In the first scenario, we compare by simulations, the convergence of the output power of the PV system under test, to the MPPT using P&O, conventional fuzzy logic and proposed fuzzy logic algorithms.

First, we fixed the temperature at 27°C and we cause a rapidly change at the level of irradiation. Figure 14 shows simulation results obtained for this first scenario.

Taking into account the variations mentioned in this scenario, the results are shown in Figure 14. For these controllers, we notice the effect of the increase of the power produced by the PV system, caused by an increase in irradiance G when the temperature is fixed. In this case, the convergence time or response time of the proposed controller is faster than the classical one.

- Performances of MPP Tracker Under Real Conditions:

For the second scenario, both control algorithms P&O and fuzzy MPPT controllers are simulated and tested on the MATLAB/Simulink environment, under illumination and temperature, modulated according to one day.

On Figures 15 and 16, we present the evolution of measured weathers conditions.

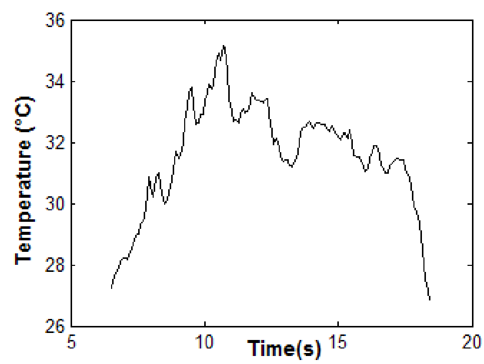

Figure 15. Temperature for a day.

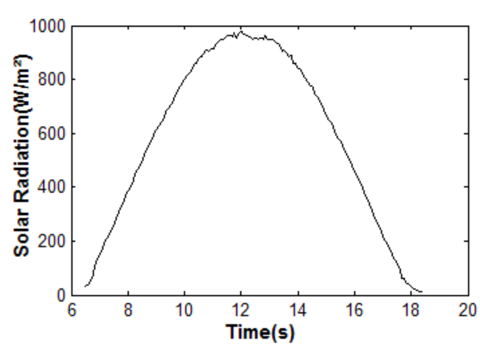

Figure 16. The solar radiation for a day.

In this section, we examine the effects of control assured by the three MPPT schemes: P&O, the conventional and the proposed fuzzy controller to variations in measured temperature and irradiance. These effects are illustrated in Figure 17; it demonstrates the high efficiency, on terms of stability and response time, the proposed controller compared to the conventional and the P&O algorithm, which validates the interpretations of first scenario.

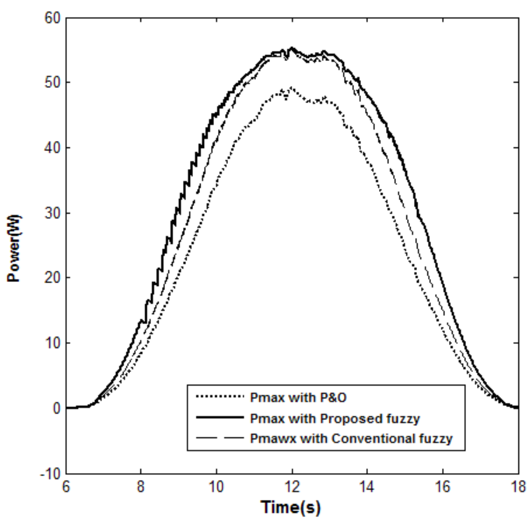

Figure 17. Maximum power obtained by P&O and fuzzy controller.

4. Experimental Results and Discussions

4.1 Description of the Hardware Setup of the System

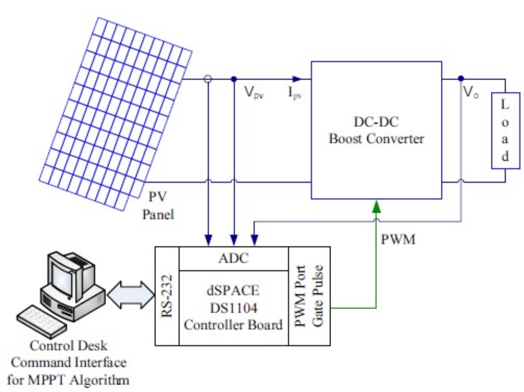

Figure 18. Structure of a PV power control system.

In this Section, we are going to simulate and test experimentally the behavior of the photovoltaic system using the developed control law combined to the presented MPPT. It has been implemented using a dSPACE carte of real-time control with a platform installed in the MIS Laboratory (see Figures 18, 19 and 20). The dSPACE carte is a powerful tool used to modify the MPPT controller parameters in real time to monitor real process.

The platform components are: A PV panel as a power source (UNI-SOLAR 62w), is connected to the DC-DC boost converter that is considered as a power process unit, a variable load and a dSPACE controller which is interfaced with a PC.

Figure 19. PV panel platform.

Figure 20. Experimental setup.

The MPPT algorithm is modeled in Simulink for dSPACE implementation. Output signals of the voltage and current transducers are sampled in dSPACE via DS1104-ADC blocks. The PWM pulses from the dSPACE are sampled via a DS1104-DSP-PWM block to produce standard 20 kHz fixed- frequency PWM pulses

4.2 Experimental Setup

In order to prove the effectiveness of the proposed fuzzy-MPPT method, a comparison between the harvested power and the one we get when using a P&O algorithm, is available in this section.

The Figures 21and 22 show real-time a data capture using Control Desk. We can see the temperature of photovoltaic cells and the solar radiation that are necessary for the conduct of the fuzzy algorithm. Also, we can see the PV current, voltage and the power produced with each MPPT algorithm.

Using P&O-MPPT Algorithm: Using Fuzzy-MPPT Algorithm:

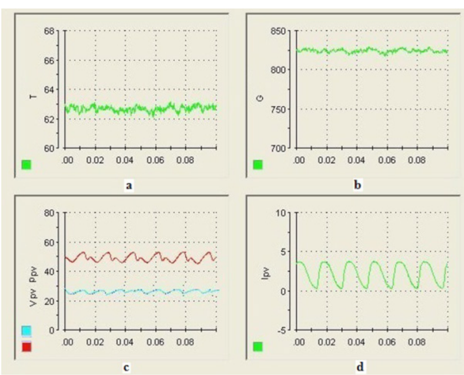

Figure 21. **(a)** Cell temperature. **(b)** Solar radiation. **(c)** Pv voltage and power. **(d)** Pv Current using P&O algorithm.

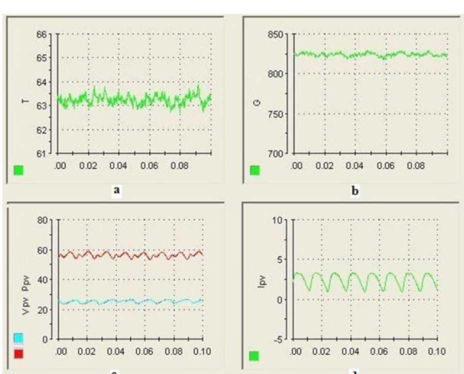

Figure 22. **(a)** Cell temperature. **(b)** Solar radiation. **(c)** Pv voltage and power. **(d)** Pv current using fuzzy algorithm.

We can see in Figure 21, the produced power by the used panel. It is around 50 W for approximately 825 W/m² sunshine and cell temperature of about 60 °C. However, there is a marked improvement in power output. It is around 57 W, meaning an increase of up to 7W or 14% compared to the previous power which is produced by the classical method.

Of course, in virtually identical weather conditions. This is possible by testing on a small period of time.

Obviously, we can say that our control law gets there pretty well, which explains the 14% gain of power.

- Implementation of the P&O-MPPT Method:

The performance of the P&O-MPPT alters according the perturbation step size. The use of a large step size may increase the tracking speed but at the same time the oscillation around MPP is increased. It's necessary to choice the correspondent step size to reach a compromise between the need for fast tracking of MPP and the oscillation around this point.

The P&O MPPT algorithm is tested under the ambient conditions shown in Figure 24.

Figures 23(b), 23(c) and 23(a) show the related voltage, current and the maximum power tracked.

We can notice that the maximum power is changed accordingly with the solar radiation variation.

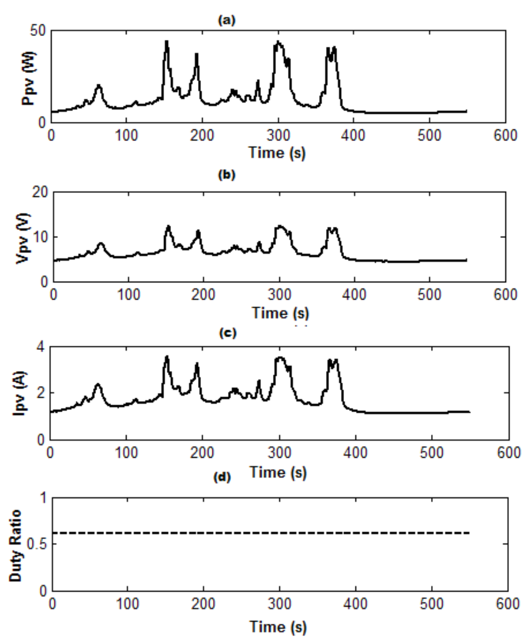

Figure 23. Experimentally tracking behavior of the P&O-MPPT.

- *Implementation of the proposed fuzzy-MPPT Algorithm*:

MPPT is an intriguing technology; this controller will harvest more power from the solar panel comparing with the classical technologies.

The principle of the proposed algorithm is to calculate the optimal reference output voltage in order to ensure that the PV system is operated at its MPP.

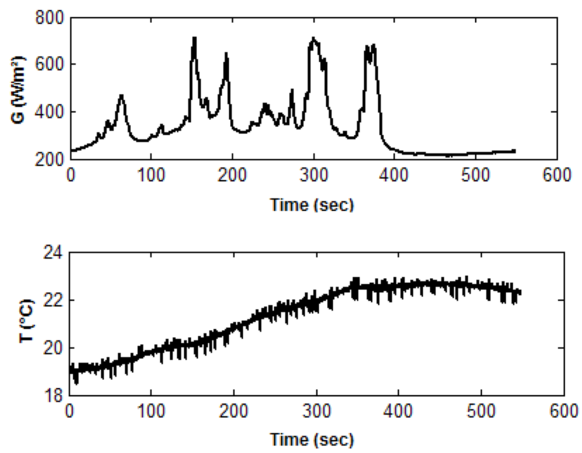

Figure 24. Changing ambient conditions.

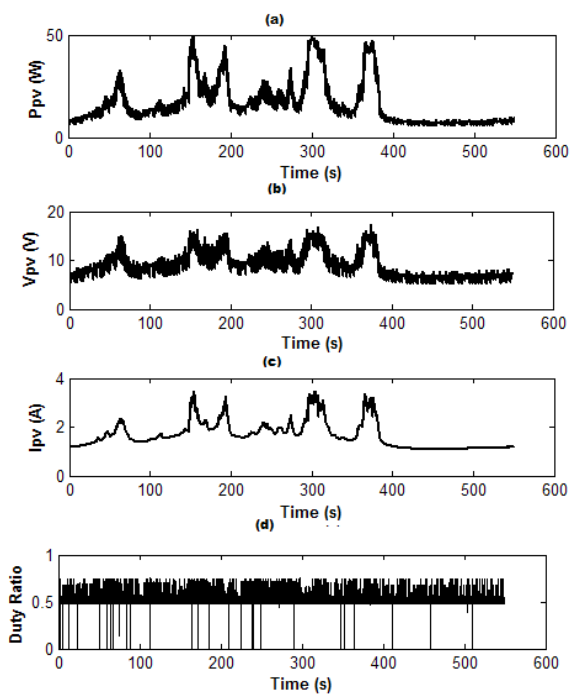

Figure 25. Experimentally tracking behavior of the Fuzzy-MPPT.

To demonstrate the effectiveness of the proposed method, the fuzzy-MPPT algorithm is implemented experimentally by adopting dSPACE 1104 data acquisition system. To track successfully the MPP, we consider the membership function of the inputs variable shown in Figures 9, 10, 11 and 12.

Table 1 indicates the FLC rules tuned for providing a better performance of the PV system.

Taking into account these changes, we tested the proposed approach under some different ambient conditions.

Figure 24 shows the variation on the solar radiation while the lower plot shows the changing in the PV temperature on 19-06-2015.

In fact, we tracked successfully the MPP of the PV module through the Fuzzy-MPPT method as shown in Figure 25. The upper plot in this Figure indicates the maximum power tracked. Figures 25(b) and 25(c) show the PV voltage and the related PV current. The duty cycle which is provided by the proposed fuzzy method is shown in Figure 25(d).

The MPPT block generates the duty cycle at the output, which is injected to the PWM in order to provide the switching pulses of the IGBT.

Effectiveness and accuracy are detected on tracking the maximum power point under variation in solar radiation. In fact, the photovoltaic power obtained by the proposed method is around 50 W for the maximum level of solar radiation, mentioned in Figure 24, meaning an increase of up 7 W compared to the previous power generated by the P&O method.

5. Conclusion

This paper presents a photovoltaic model adopting MATLAB/SIMULINK and illustrates the conception of the suitable boost converter related to a maximum power tracker. The proposed fuzzy-MPPT method has been implemented under disturbance in the photovoltaic irradiation levels.

Throughout these tests, we have been able to make some convincing conclusions. Unlike fuzzy MPPT which is able to instantly track the new maximum power point, P&O MPPT doesn't allow maximum tracking of power point in case of abrupt fluctuation of irradiation or temperature. This drawback is absolutely absent when it comes to fuzzy-MPPT which tracks almost instantly new maximum power point.

Experimental tests showed that for the same weather conditions, the produced PV power by the P&O-MPPT algorithm is 14% less than the power produced when the fuzzy algorithm is used.

The simulations results show that the suggested controller accurately and successfully pursues the maximum power under real atmospheric conditions. The execution of real time control setup of the MPPT hardware uses the dSPACE.

6. References

1. Faranda R, Leva S. Energy comparison of MPPT techniques for PV systems. Wseas Transactions on Power Systems; 2008 Jun.
2. Kanth MK, Kishore DR. Implementation of MPPT techniques for a high step-up converter with voltage multiplier module based photovoltaic system. Indian Journal of Science and Technology. 2015 Sep; 8(23):1–6.
3. Shiau J-K, Wei Y-C, Chen B-C. A study on the Fuzzy-logic-based solar power MPPT algorithms using different fuzzy input variables. Algorithms. 2015; 8(2):100–27.
4. Solas V, Olias E, Barrado A. Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems. Solar Energy Materials and Solar Cells. 2006; 90:1555–78. Crossref
5. Ammasai N, Peter SA, Nallandula H, Krithiga S. Fuzzy logic controller with MPPT using line-commutated inverter for three-phase grid-connected photovoltaic systems. Energy. 2009; 34:909–15.
6. Mohammad TKN, Islam MA, Hossain QD. Improved solar photovoltaic array model with FLC based maximum power point tracking. IJECE. 2012 Dec; 6:717–30. Crossref
7. Levron Y, Shmilovitz D. Maximum power point tracking employing sliding mode control. IEEE Transactions on Circuits and Systems. 2013 Mar; 60.
8. Mohamed AAS, Berzoy A, Mohammed O. Optimized-fuzzy MPPT controller using GA for stand-alone photovoltaic water pumping system. 2014 Nov.
9. Letting LK, Munda JL, Hamam Y. Optimization of fuzzy logic controller design for maximum power point tracking in photovoltaic systems. Soft Comput in Green and Renew Ener Sys; 2011.
10. Radjai T, Gaubert PJ, Rahmani L. The new FLC-variable incremental conductance MPPT direct control method using cuk converter. Proceedings of the 2014 IEEE 23rd International Symposium on Industrial Electronics (IEIE); Istanbul, Turkey. 2014 Jun 1-4. p. 2508–13. Crossref
11. Rahmani R. Seyedmahmoudian M, Mekhilef S, Yusof R. Implementation of fuzzy logic maximum power point tracking controller for photovoltaic system. Am J Appl Sci. 2013; 10:209–18. Crossref
12. Cheikh MSa, Larbes C, Kebir TGF, Zerguerras. A maximum power point tracking using a fuzzy logic control scheme. Revue Energ Renouv. 2007; 10:387–95.
13. Chin CS, Neelakantan P, Yoong HP, Teo KTK. Optimisation of fuzzy based maximum power point tracking in PV system for rapidly changing solar irradiance. Trans Sol Energy Plan. 2011; 2:130–7.
14. Liu C-L, Chen J-H, Liu Y-H, Yang Z-Z. An asymmetrical fuzzy-logic-control-based MPPT algorithm for photovoltaic systems. Energies. 2014; 7(4): 2177–93. Crossref
15. Khateb AHE, Rahim NA, Selvaraj J. Type-2 fuzzy logic approach of a maximum power point tracking employing sepic converter for photovoltaic system. J Clean Energy Technol. 2013; 1:4144.
16. Takun P, Kaitwanidvilai S, Jettanasen C. Maximum power point tracking using fuzzy logic control for photovoltaic systems. International Muti Conference of Engineers and Computer Scientists; Hong Kong, China. 2011 Mar; 16-18.
17. Putri RI, Wibowo S, Taufi M, Taufik. Fuzzy incremental conductance for maximum power point tracking in photovoltaic system. IJESIT. 2014; 3:352–9.
18. Sakly A, Ben Smida M. Adequate fuzzy inference method for mppt fuzzy control of photovoltaic systems. Proceedings of the 2012 International Conference on Future Electrical Power and Energy systems, Lecture Notes in Information Technology; 2012. p. 457–68.
19. Tina GM, Ventura C. Evaluation and validation of an electrical model of photovoltaic module based on manufacturer measurement. Springer-Verlag Berlin Heidelberg; 2013.
20. Doumis AI, Kofinas P, Alafodinos C, Tseles D. Adaptive fuzzy gain scheduling PID controller for maximum power point tracking of photovoltaic system. Renewable Energy. 2013; 60:202–14. Crossref
21. Pandiarajan N, Muthu R. Mathematical modeling of photovoltaic module with simulink. International Conference on Electrical Energy Systems (ICEES 2011); 2011 Jan 3-5.
22. Esram T, Chapman PL. Comparison of photovoltaic array maximum power point tracking techniques. IEEE Transactions on Energy Conversion. 2007; 22(2):439–49. Crossref
23. Koutroulis E, Kalaitzakis K, Voulgaris NC. Development of a microcontroller based photovoltaic maximum power point tracking control system. IEEE Transactions on Power Electronics. 2001; 16(1):46–54. Crossref
24. Selvan S, Kumar G, Umayal. Comparative study of perturb an observe and fuzzy logic control based MPPT algorithms. International Journal of Advances in Engineering and Technology. 2015 Jan.