A PSO-BASED OPTIMIZATION OF A FUZZY-BASED MPPT CONTROLLER FOR A PHOTOVOLTAIC PUMPING SYSTEM USED FOR IRRIGATION OF GREENHOUSES

A. HADJAISSA, K. AMEUR, M. S. AIT CHEIKH AND N. ESSOUNBOULI

Abstract. The main asset of this paper is among the uses of fuzzy logic in the engineering sector and especially in the renewable energies as a large alternate of fossil energies, in this paper a PSO-based optimization is used to find the optimal scaling parameters, of a fuzzy logic-based MPPT controller, that maximize the efficiency of a photovoltaic pumping system. The tuning of input and output parameters are of direct effect on the power that flows from the photovoltaic source to the load. In order to see concrete results, the PV system is used for irrigation of greenhouses in Laghouat, Algeria. The performances of the proposed PSO-based fuzzy controller are compared with those obtained using fuzzy logic and P&O controllers under variations of meteorological conditions. The simulation results proved a good robustness performance of the proposed Fuzzy based PSO controller over the other regarding the gained solar energy and the daily pumped water.

1. Introduction

Crop irrigation in arid areas, where there is no enough rain, presents a major problem and renders agriculture very difficult.The only solution to this problem is by pumping the ground water into a storage tank. This operation consume a lot of electric energy, which is not available in remote farms, especially in our region Laghouat, Algeria. To overcome the lack of electricity, and reduce the environment pollution effect, renewable energy sources can play the perfect solution. The choice of one source or more depends on its abundance in the region; hence, the photovoltaic energy has been chosen to meet our pumping system requirements [8]. Even though the photovoltaic power is clean, renewable, and economical source of electricity in remote areas, it has two major drawbacks; the non-availability of the power during darkness periods, and its non-linearity behavior, and therefore solutions are needed. In most photovoltaic pumping systems, the water is pumped into tanks during the presence of sunlight and used when needed during darkness periods[6]. To deal with the non-linearity of the source, a dc-dc converter, controlled by an MPPT algorithm, is inserted between the source and the load. The MPPT algorithm is a technique that allows the dc-dc converter to get the maximum possible power the PV source can provide, and therefore the performance of

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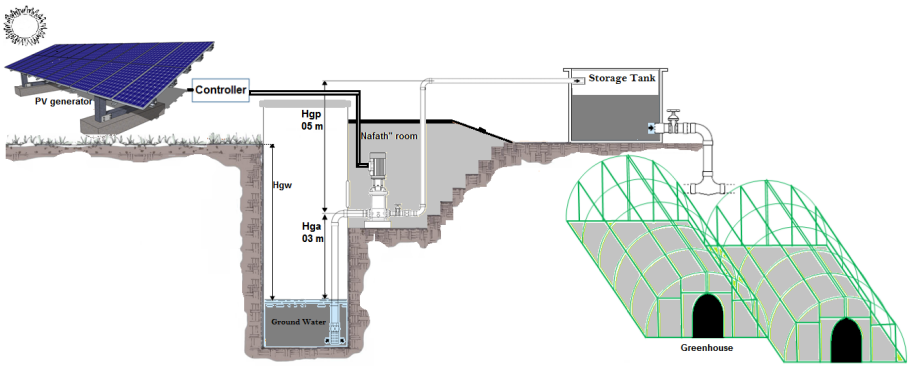


FIGURE 1. PV Irrigation Pumping System

converter is strongly related to how good and robust is the algorithm[1]. In order to extract the maximum energy of photovoltaic generator, a boost DC_DC inverter which allows to adapt the voltage of panels to have the maximal point of power, this later has been added between the source and the load, and controlled by the MPPT algorithm.

The choice of boost inverter is justified by the value of nominal voltage of motor-pump is higher than the voltage of the photovoltaic generator, even the sizing of boost inverter has been made on a conversion ratio of 0.5 , the point where the performance of converter is maximum (at the standard condition $1000w/m^2$,$25°C$, AM1.5). In literature, many MPPT techniques exist such as: Incremental conductance, Pilot Cell, constant voltage and current, P&O, and fuzzy logic-based algorithm[1,2]. The latter has proved a strong robustness against the meteorological changes. Its difficulty resides in the choice of the rules and the tuning of input and output ranges [3,9].

The simulation of photovoltaic pumping system is madded by the three controllers P&O,FL MPPT and MPPT FL-PSO, under an irradiance can simulate the daily irradiance, with the brutal change in order to test the robustness and response time of controllers. In this work, and in order to give a remedy to the a fore mentioned problem, a Fuzzy logic-based MPPT algorithm, optimized by using Particle Swarm Optimization PSO, is provided [5,7].

2. **Sizing of the PV Pumping System**

The pumping system has been designed for irrigation of tomato greenhouses. It is composed of three main parts: PV panels, a motopump, and a storage tank. Figure 1 shows a simple schematic of the pumping system.

2.1. **Storage Tank Sizing.** The estimated maximum daily water requirements for one square meter of tomatoes is $R_{to} = 16\, l/m^2/day$. In addition, all the planted area is $S_{gh} = 900\, m^2$ divided into 10 greenhouses of $(18 \times 5)\, m^2$, hence the daily water needs can be calculated as follow, equation(1):

$$V_{wt} = S_{gh} \times R_{to} = 14.4\, m^3/day \tag{1}$$

Taking into consideration water evaporation and storage tank losses, the capacity of the tank is set at $C_{tk} = 16\,m^3$.

2.2. **Motopump Sizing.** Pump sizing relies on three parameters: tank volume C_{tk}, the least average number of Peak Sun Hours per day (L_{ps}) during each month of one year at Laghouat, and Total Dynamic Head (TDH).

2.3. **Least Average Number of Peak Sun Hours Per Day** (L_{ps})**.** Due to lack of meteorological station in Laghouat city, a theoretical Liu & Jordan model has been used for irradiance estimation.

This model provides a complex analytical relationship for theoretical solar irradiation. It needs only the location latitude, and it can compute solar irradiation for different plan angles. The geographical coordinates for the site selected for solar array installation are Latitude: 33.806°, and Longitude: 2.882°. In this analysis MATLAB was used to compute the hourly Global Horizontal Irradiance (GHI), and Global Tilted Irradiance (GTI) as well, for each day of the year, and then to calculate the daily solar-energy density for both of them by numerical integration (see Figure 2). GHI is measured on a horizontal plane; whereas GTI is measured

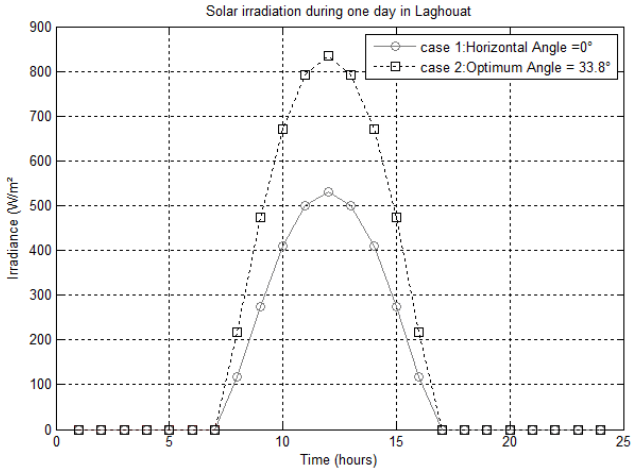


FIGURE 2. Theoretical Solar Irradiation During One Day (23 December) in Laghouat, Algeria

on a plane faces due south and tilted at yearly optimum angle Y_{OAT}, equation(2). The latter is calculated as follow :

$$Y_{OAT} = \frac{\sum_{j=1}^{365} D_{OAT}}{365} \tag{2}$$

Where:
D_{OAT} is the daily optimum angle of tilt, which varies during one year according to the following, equation(3):

$$D_{OAT} = (latit) - asin(0.4 \times sin(\frac{N_{day} \times 360}{365})) \tag{3}$$

N_{OAT} : the number of days. The 21^{st} of March is considered as the first day.

Figure 3 shows the variation of the optimum angle of tilt per day D_{OAT} during one year in Laghouat. The Y_{OAT} is equal to 33.8°. Monthly values for total solar

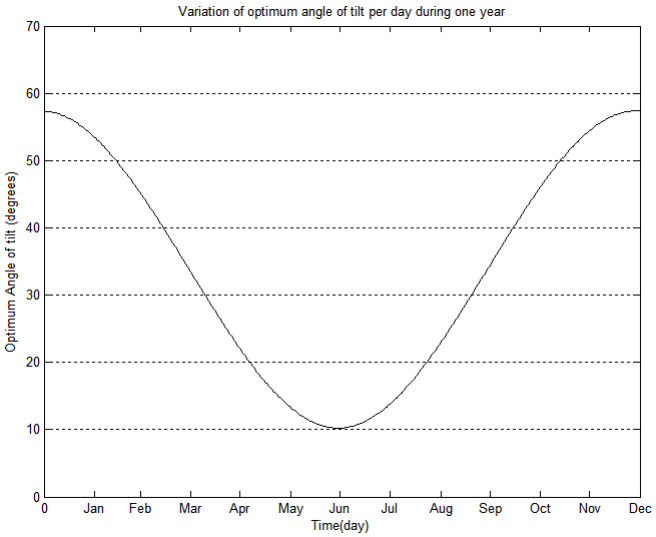


FIGURE 3. Variation of the Optimum Angle Per Day During One Year

energy density were divided by the number of days in each month to determine the mean daily solar energy density. These values are shown in Figure.4. Then, data

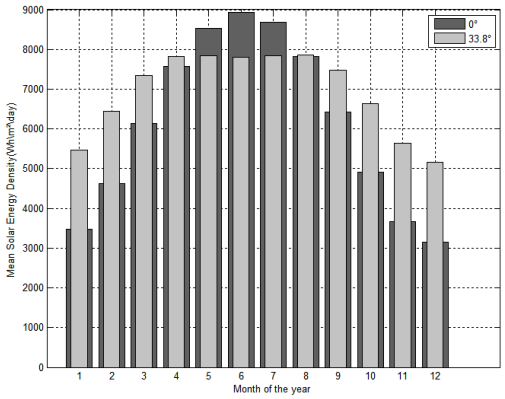


FIGURE 4. Mean Daily Solar Energy Density by Month in Laghouat, Algeria

of figure 4 were used, as well, to determine the mean number of peak sun hours Hps per day during each month. It is defined as number of hours at an irradiance level of $1\,kW/m^2$ required to produce the total solar energy density available in one day.

Peak sun hours are an indicator of how many hours per day solar arrays will operate at peak power output. Table 1 shows the mean daily peak sun hours during each month.

Month	**Hps for horizontal plane(hours/day)**	**Hps for tilted plane** $Y_{OAT} = 33.8°$ **(hours/day)**
January	3.47	5.46
February	4.61	6.43
March	6.13	7.35
April	7.58	7.82
May	8.52	7.84
June	8.93	7.81
July	8.68	7.83
August	7.81	7.85
September	6.43	7.48
October	4.90	6.64
November	3.66	5.54
December	3.15	**5.16**
Annual average	**6.16**	**6.94**

TABLE 1. Mean Number of Peak Sun Hours Par Day During Each Month in Laghouat

To ensure the pumping of the needed water all year around, the sizing of the PV generator must be set basing on the least number of peak sun hours L_{psh}.

2.4. **Total Dynamic Head (TDH).** TDH, equation(4), is the total equivalent height that a fluid is to be pumped at, taking into account friction losses in the pipe and hydraulic accessories:

$$TDH = H_{gp} + H_{ga} + F_L \tag{4}$$

Where:
H_{gp} = (Static Height) is the maximum height reached by the pipe after the pump (see figure. 1).
H_{ga} = (Static Lift) is the height the water will rise before arriving at the pump.
F_L = is the friction losses.

According to the Department of Agriculture and Rural Development in Laghouat, groundwater exists, in some places along the River Mzi (a river that flows next to Laghouat city) at a depth over five meters (Hgw).

In order to reduce the photovoltaic system cost and even the pump maintenance, a centrifugal surface pump is used. Its main drawback is that operate at a suction lift of maximum "H" meters head, beyond this limit the pump may have cavitation problem.

To make the pump operate under the permitted suction lift, Nafath room (generally, a tunnel that leads to the bottom of the well) was built as shown in Figure 1. In addition, this room facilitate the maintenance of the pump.

Taking $H_{ga} = 03\,m$, $H_{gp} = 05\,m$, and $F_L = 0.16\,m$, equation(4) become equation (5) :

$$TDH = 08.16\,m \tag{5}$$

To ensure the filling of the $16\,m^3$ tank, in less than 5.16 hours, the machine has to pump about $3\,m^3/h$ at a height greater than 08.16 m.

However, the ideal hydraulic power requirement for the pump can be calculated by equation(6):

$$P_{H_req}(W) = \frac{g(m/s^2)\times\rho(Kg/m^3)\times Q(m^3/h)\times TDH(m)}{3600} \tag{6}$$

Where:

P_{H_req} = power (W)
Q = flow rate (m^3/h)
ρ = density of fluid (kg/m^3)
g = gravity $(9.81\,m/s^2)$

The electric power required for the motopump, depends on the efficiency of the pump and the motor can be calculated by equation(7):

$$P_{E_req}(W) = \frac{P_{H_req}(W)}{\eta_p \times \eta_m} \tag{7}$$

Where:

η_p = pump efficiency
η_m =motor efficiency

2.5. **PV Generator Sizing.** Taking into consideration the least number of peak sun hours per day L_{psh} and the power losses in cables and connections L_{CC}, the necessary energy, equation(8), that PV generator (PVG) have to produce is:

$$E_{PV}(Wh) = P_{E_req}(W) \times L_{psh}(h) \times L_{cc} \tag{8}$$

The number of panels, used to produce this energy, depends on their peak power P_p . The maximum power of the PVG, depends on irradiance and temperature, can be reached only when the load characteristic crosses the PVG's on maximum power point MPP (Figure.5). This latter is a hard-to-reach condition.

In ordre to follow the MPP, a maximum power point tracker MPPT is used.

3. MPPT Controller

It is composed of both hard and soft parts (Figure.6): the dc-dc converter and the algorithm of MPP tracking.

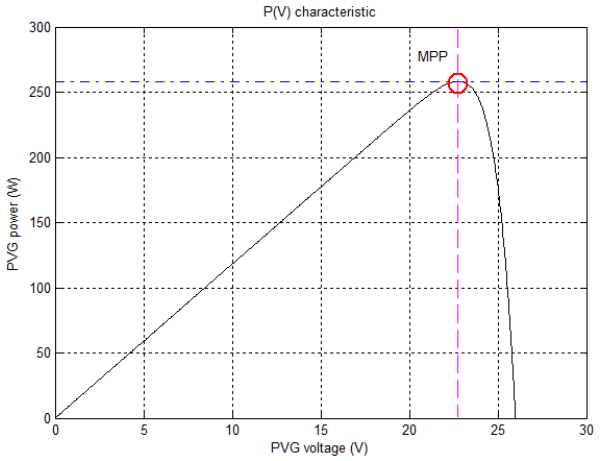


FIGURE 5. P-V Curve

3.1. **dc-dc Converter.** As the load operating voltage is greater than the PVG's, at the MPP, the dc-dc converter is chosen to be a Boost converter. The power switch is responsible for modulating the energy transfer from the input source (PVG) to the load (motopomp) by varying the duty cycle D.

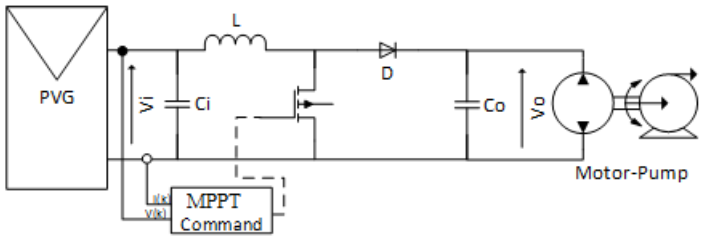


FIGURE 6. dc-dc Converter Circuit

The relationship between the input voltage and the output is given by the equation(9):

$$V_o = \frac{V_i}{1 - D} \tag{9}$$

with D is a duty cycle.

3.2. **Perturbation and Observation Method (P&O).** Due to its robustness, simplicity and ease of implementation, the P&O method is the most widely applied method in PV industry. It is based on the idea of introducing perturbation to the operating voltage and observing whether the power increases or decreases.

If the power increases, that means the perturbation is the right direction to get closer to the MPP, so the algorithm will continue in the same direction until it

reaches the MPP, Figure 5. When the perturbation goes to the other side (right or left) of the curve summit, the power decreases and the algorithm will change the direction of the perturbation to the opposite side.

3.3. **Fuzzy Logic and PSO-based Fuzzy Logic Controllers.** FLC has been introduced in many researches as an alternative to conventional control techniques that are based on complex mathematical models. The basic idea behind FLC is to combine the expert experience of a human operator with the design of the controller that does'n need any mathematical model. FLC can be presented as a box (process) whose input-output relationship is described by collection of fuzzy control rules (e.g., IF-THEN rules) involving linguistic variables rather than a complicated dynamic model.

In this paper, the inputs are the error, equation(10):

$$\varepsilon(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{10}$$

which represents the slope of the curve P(V). and the change of error, equation(11):

$$\Delta\varepsilon(k) = \varepsilon(k) - \varepsilon(k-1) \tag{11}$$

which is the difference between the error at k_{th} instant and that of $(k-1)_{th}$ instant.

The output represents the value of the duty cycle sampling $dD(k)$.

The membership functions of inputs and output of fuzzy logic controller before optimization is presented in Figures 7, 8 and 9.

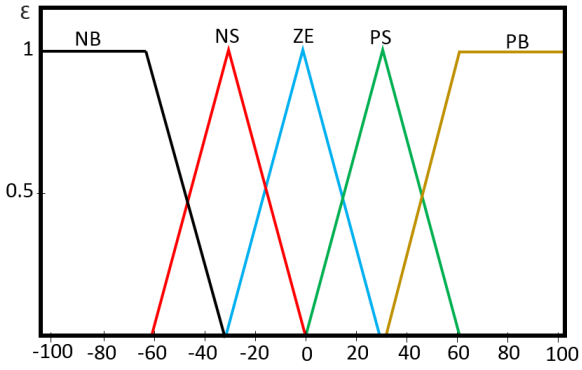


FIGURE 7. Membership Function of error ε

The control rules are indicated in Table 2 with $\varepsilon(k)$ and $\Delta\varepsilon(k)$ as inputs and $\Delta D(k)$ as the output.

The surface rules of fuzzy logic controller is presented in figure 10.

As mentioned above, the FLC needs an expert to define its rules and ranges, and in most of cases the results can be seen good but not optimal.

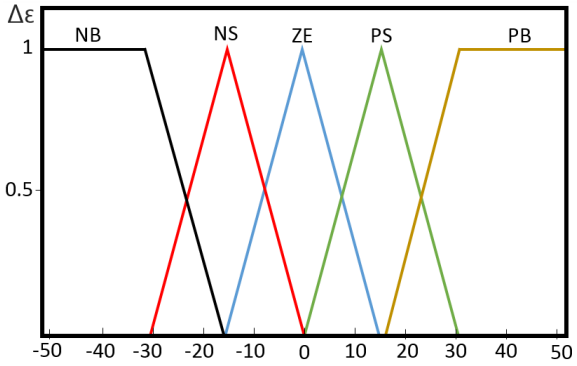


FIGURE 8. Membership Function of Change of Error $\Delta\varepsilon$

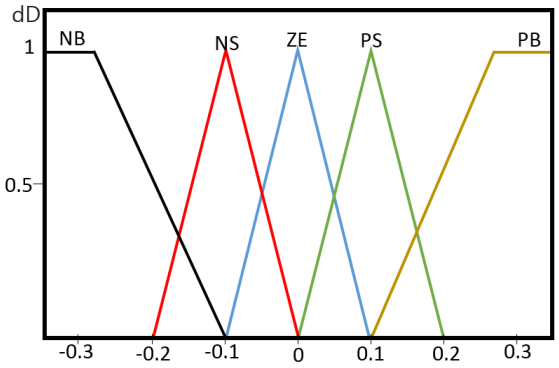


FIGURE 9. Membership Function of Sampling Duty Cycle ΔD

$\Delta\varepsilon(k) \Downarrow / \varepsilon(k) \Longrightarrow$	NB	NS	ZE	PS	PB
NB	PB	PB	PS	NB	NB
NS	PS	PS	ZE	NS	NS
ZE	PS	PS	ZE	NS	NB
PS	ZE	ZE	NS	NS	NB
PB	ZE	ZE	NS	NB	NB

TABLE 2. Fuzzy Rule Table

In this work, we proposed a technique based on Particle Swarm Optimization in order to get the optimal performance of the FL controller.

The description of steps of a PSO algorithm in order to optimized the fuzzy logic controller gains are the following :

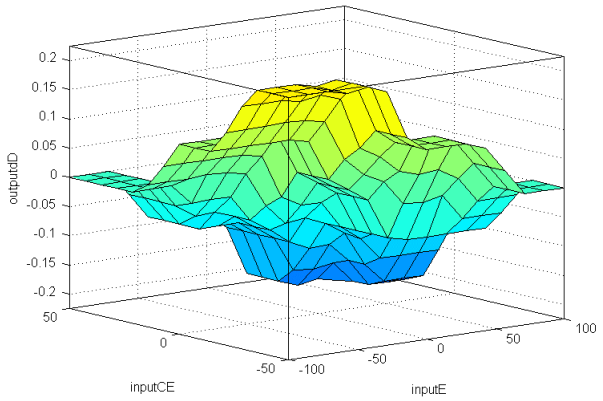


FIGURE 10. Surface Rules of Fuzzy Logic Controller

{
For each particle
{
Initialize particles (randomly)
}
Do until maximum iterations
{
For each particle
}
Calculate Data fitness value: Energy (Wh) calculated by numerical trapezoidal integration.
If the fitness value is better than pBest
{
Set pBest = current fitness value
}
Else pBest is better than gBest
{
Set gBest = pBest
}
{
For the best particle
{
Calculate particle Velocity
Use gBest and Velocity to update particle Data
}.

Figure 11 depicts the PSO-based technique, applied to the FL controller.

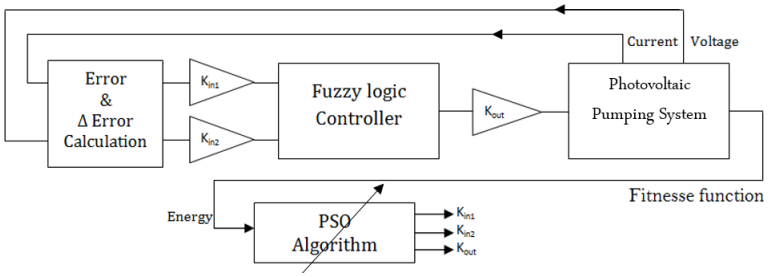


FIGURE 11. Fuzzy Based PSO Technique

The PSO algorithm, searches the optimal performance of the FLC by tuning the parameters K_{in1}, K_{in2}, and K_{out} which represent a particle in the algorithm.

The identification of the energy (Wh) has been calculated by numerical trapezoidal integration of generated power(W) by photovoltaic pumping system, as a function of time, for each iteration.

The fitness function (S) is calculated by the following, equation(12):

$$Max(S(P,h)) = \frac{h}{2}(P(t_0) + P(t_1)) + h\sum_{k=1}^{m} P(x_k) \tag{12}$$

with:

- P:is the power energy.
- t_0 and t_1 : is initial and final time interval of trapezoidal integral calculation.
- m : is number of subintervals $[x_{k-1}, x_k]_{k=1}^{m}$
- $h = \frac{t_1 - t_0}{m}$

4. **Simulation and Results**

In this section we present the results of the whole system (Figure.12) using P&O, fuzzy logic and PSO-based FL control techniques to track the maximum power point under a variation of the irradiance.

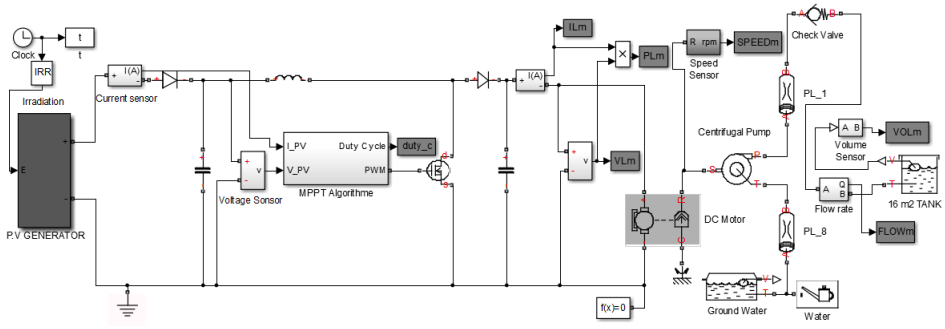


FIGURE 12. Pumping System with MPPT Connection of the PVG

This figure is the association of four stages, most of MPPT controller:

-First stage is the photovoltaic generator with an optimum power point of 255W at the standard conditions.

-The second, is the boost converter in order to boost the voltage to the load.

-The third stage is the DC motor in order to drives the centrifugal pump.

-The last stage is the pump for pumping water from the well to the tank.

The membership functions of inputs and output of fuzzy logic controller after optimization is presented in Figures 13, 14 and 15.

For more details on the used parameters and the simulation results in the algorithm PSO see Appendix.

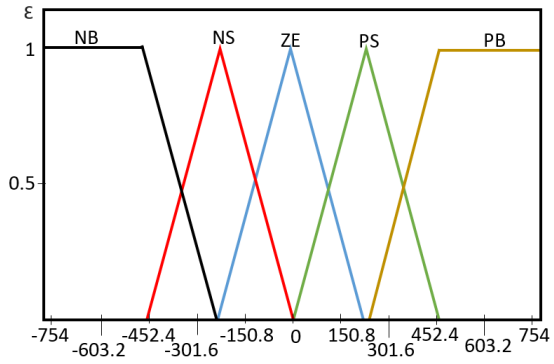


FIGURE 13. Optimized Membership Function of Error ε

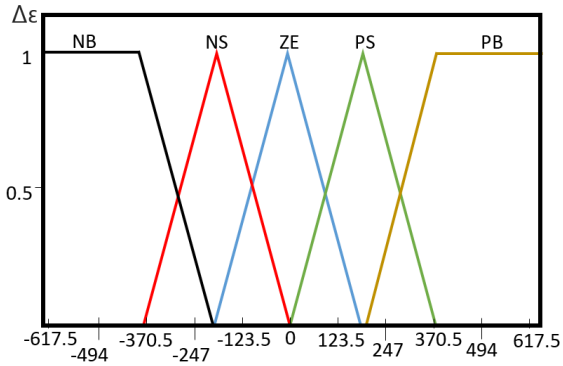


FIGURE 14. Optimized Membership Function of Change of Error $\Delta\varepsilon$

All the following results were implemented in Matlab/ Simulink environment using Sim-Electronics and Sim-Hydraulics block sets.

The following results are obtained under variable irradiance (Figure.16) and a temperature of $25°C$.

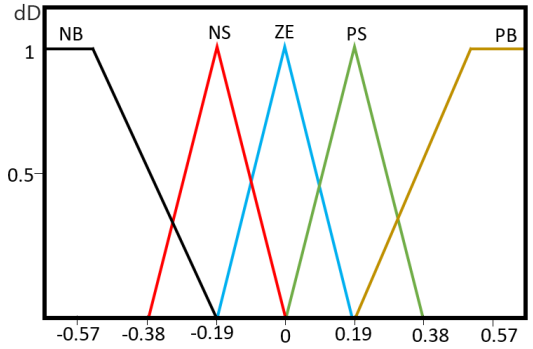


FIGURE 15. Optimized Membership Function of Sampling Duty Cycle ΔD

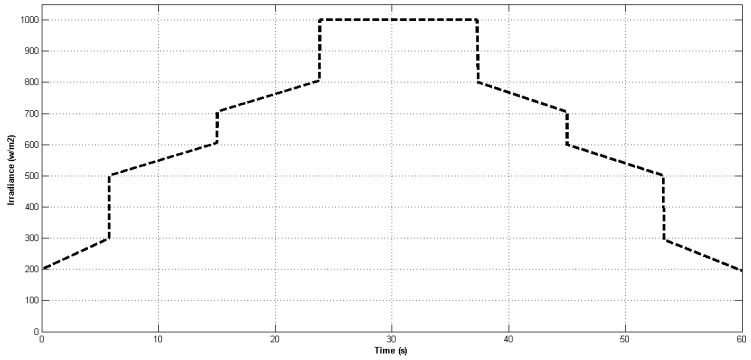


FIGURE 16. Irradiance Variation

As illustrated in Figures 17, 18 and 19, the current, voltage and power of the PVG, respectively, have the same shape as the irradiance curve. This means that they are directly proportional to the irradiance.

We note in some cases the big difference in power, between the three systems, that can reach up a $40\,W$.

We observe also that in case of sudden high and positive variations of the irradiance, our proposed PSO-based algorithm reacts quickly and faster than the other tow.

Figure 20 shows the speed of motopump, which depends directly to the PVG voltage.

In Figure 21, the water flow starts when the motopump reaches a specific speed, around 1750 rpm, and then varies according to its variation.

Figure 22 illuminates that difference, between the three controllers, by the amount of pumped water.

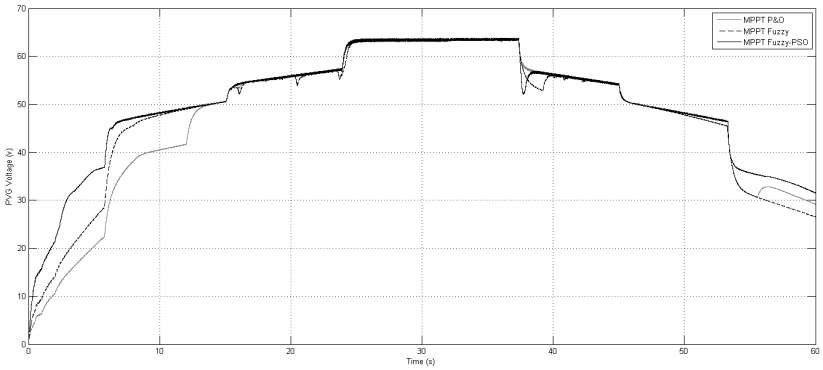


FIGURE 17. Variation of the PVG Voltage

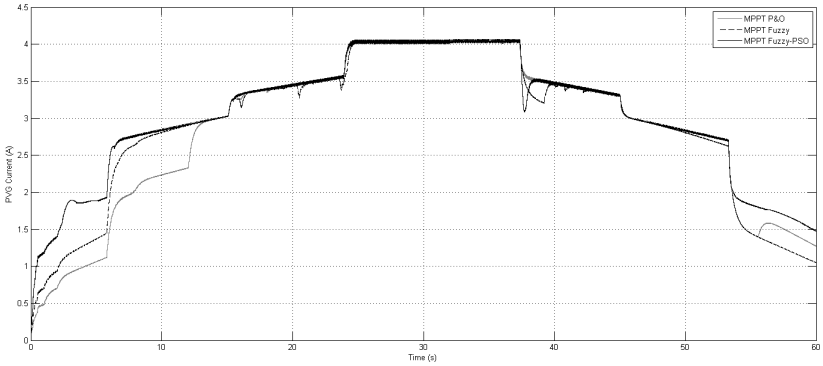


FIGURE 18. Variation of the PVG Current

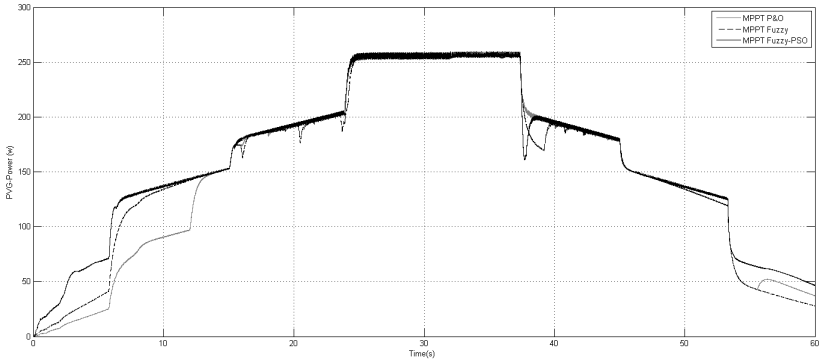


FIGURE 19. Variation of the PVG Power

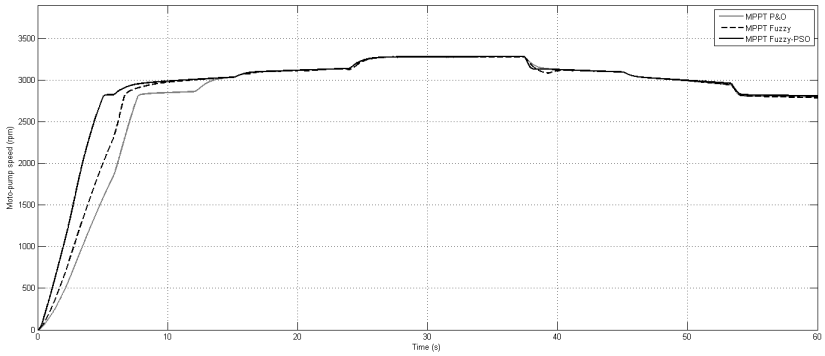


FIGURE 20. Variation of the Motopump Speed

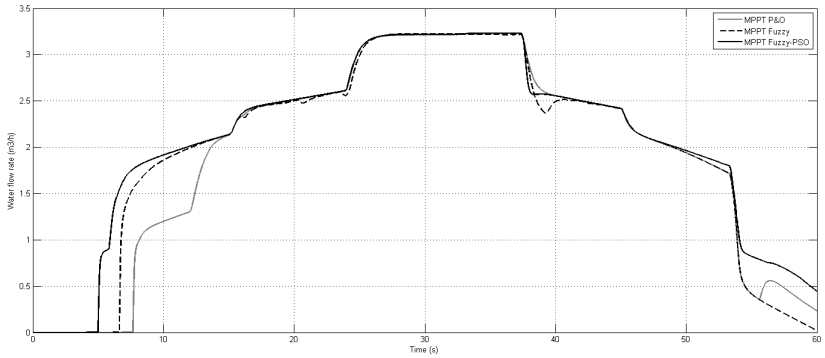


FIGURE 21. Variation of the Water Flow Rate

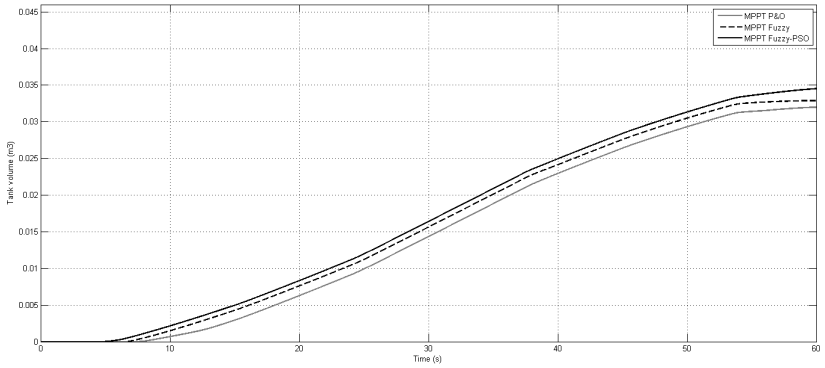


FIGURE 22. Progress of the Tank Volume

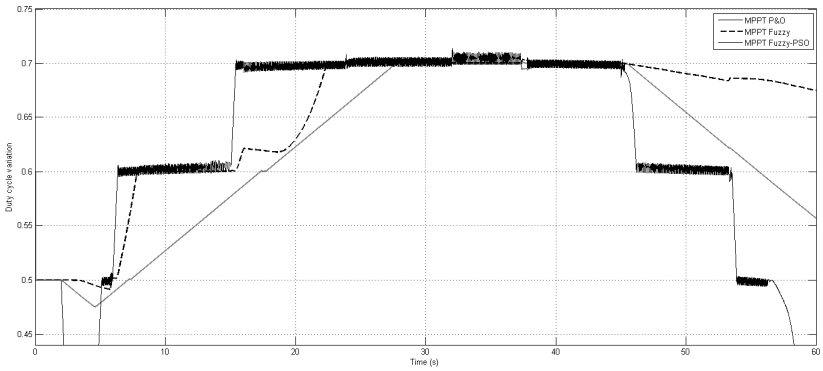


FIGURE 23. Duty Cycle Variation

Figure 23 represents the variation of the duty cycle. At the beginning, the duty cycle was fixed at 0.5, then and after passing the transient mode, all three algorithms started calculating the duty cycle depending on the PVG power and voltage.

In order to confirm that the controllers track the maximum power point, we compare the P-V curve Figure 5 at the point of maximum power ($\backsimeq 253W$), with the power in Figure 19 between 25s and 37s,in some conditions.

Table 3 depict the summary of essential results quantity, for all controllers: all parameters have been calculated by the numerical trapezoidal integration, in one minute of time.

Parameters	P&O	FL	FL-PSO
Power(w)	$9.0577e^{03}$	$9.2708e^{03}$	$9.6700e^{03}$
Flow(m3/h)	115.1771	118.3621	124.2823
Volume(m3)	0.8955	0.9584	1.0021

TABLE 3. Simulation Results

It is observed that the PSO-based controller has a better response time than of the fuzzy logic and P&O controllers. In addition,the big response time in P&O affect the transferred power and may cause little power loss. On the contrary, the PSO-based fuzzy and fuzzy logic algorithm have fast response time therefore no power losses happened.

5. **Conclusion**

This paper represents a leading work on the field of pumping systems in Laghouat, Algeria. A complete study has been done for estimating the captured energy per day, calculating the daily needed water for greenhouses, measuring the ground water depth, and sizing the pump.

The main advantage of the MPPT controller based fuzzy logic is the response time and the robustness to the brutal changes (cloud, tunnel for a hybrid car ... etc.) this controller is best compared to a MPPT controller type P&O, this improvement has a direct effect on the quantity of pumped water .

This advantage due that the fuzzy controller based directly and taking the decision following the inputs and the inference table, but the P&O controller based on the perturb and the observe to have a decision on the command, during the time of perturb there loss lot of energy.

Moreover, considerable improvements have been made to the whole system, and are summarized in the two following main points:

- Reducing the system cost and easing the motopump maintenance by adopting the idea of Nafath room, and choosing a surface pump.
- Improving the system efficiency by using PSO-based fuzzy logic controller.

The obtained results bear witness to the good function of the pumping system; Basing on the gained amount of water a day $33\,m^3$ compared by MPPT P&O, and $13.5\,m^3$ compared with MPPT fuzzy logic, the proposed algorithm can provide and reflects the considerable improvement brought by the PSO-based fuzzy controller to pumping system.

6. **Appendix**

Particle Swarm Optimization simulation parameters:
✓Number of variables: 3.
✓Number of particles in the swarm : 10.
✓Number of iterations: 10.
✓Initial range of first variable: [0.1 , 50].
✓Initial range of second variable: [0.1 , 20].
✓Initial range of third variable: [0.01 , 5].
✓initial swarm matrix:

40.7547	3.2365	3.2821
45.2990	19.4148	0.1882
6.4366	19.1476	4.2472
45.6775	9.7590	4.6706
31.6547	16.0256	3.3969
4.9673	2.9235	3.7911
13.9971	8.4930	3.7182
27.3894	18.3231	1.9672
47.8796	15.8649	3.2808
48.2479	19.1939	0.8642

✓Best swarm matrix :

37.5882	16.8303	1.7648
12.8292	5.1602	4.1558
25.3473	16.3043	2.9305
34.9839	4.9461	2.7531
44.5561	18.5923	4.5868
47.9686	7.0647	1.4363
27.4061	4.0122	3.7884
7.0174	5.0966	3.7711
7.5498	**12.3593**	**1.9084**
12.9497	9.5184	2.8434

✓Best particle 9th in Best swarm matrix :
[7.5498 12.3593 1.9084]
✓simulation time : 11827s.

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