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

A. HADJAISSE, 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 alternative 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
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 1000 w/m², 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 $R_{to} = 16 l/m²/day$. In addition, all the planted area is $S_{gh} = 900 m²$ divided into 10 greenhouses of $(18 \times 5) m²$, hence the daily water needs can be calculated as follow, equation (1):

$$V_{wt} = S_{gh} \times R_{to} = 14.4 m³/day$$

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

$$Y_{OAT} = \frac{\sum_{j=1}^{365} D_{OAT}}{365}$$  \hspace{1cm} (2)

Where:

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

$$D_{OAT} = (\text{latit}) - asin(0.4 \times sin(N_{day} \times \frac{360}{365}))$$  \hspace{1cm} (3)
\(N_{OAT}\): the number of days. The 21\textsuperscript{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 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 of figure 4 were used, as well, to determine the mean number of peak sun hours \(H_{ps}\) per day during each month. It is defined as number of hours at an irradiance level of 1\(\text{kW/m}^2\) 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.

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

Table 1. Mean Number of Peak Sun Hours Per 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:

$$TDH = H_{gp} + H_{ga} + F_L$$  \hspace{1cm} (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 $H_{ga} = 0.3 \text{ m}$, $H_{gp} = 0.5 \text{ m}$, and $F_{L} = 0.16 \text{ m}$, equation (4) become equation (5):

$$TDH = 0.816 \text{ m}$$

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 0.816 m.

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

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

Where:
- $P_{H,req} =$ power (W)
- $Q =$ flow rate ($m^3/h$)
- $\rho =$ 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):

$$P_{E,req}(W) = \frac{P_{H,req}(W)}{\eta_p \times \eta_m}$$

Where:
- $\eta_p =$ pump efficiency
- $\eta_m =$ 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:

$$E_{PV}(Wh) = P_{E,req}(W) \times L_{psh}(h) \times L_{cc}$$

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 order 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.
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.

\[ V_o = V_i \frac{1}{1 - D} \]  

where 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):

\[ \varepsilon(k) = \frac{P(k) - P(k - 1)}{V(k) - V(k - 1)} \quad (10) \]

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

\[ \Delta \varepsilon(k) = \varepsilon(k) - \varepsilon(k - 1) \quad (11) \]

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 \( \varepsilon \)]

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.
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:

<table>
<thead>
<tr>
<th>$\Delta e(k)$</th>
<th>$e(k)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
</tr>
<tr>
<td>NS</td>
<td>NB</td>
</tr>
<tr>
<td>ZE</td>
<td>NB</td>
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<td>PS</td>
<td>NB</td>
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<tr>
<td>PS</td>
<td>PS</td>
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<tr>
<td>PB</td>
<td>PS</td>
</tr>
<tr>
<td>ZE</td>
<td>PS</td>
</tr>
<tr>
<td>NS</td>
<td>PS</td>
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<td>NB</td>
<td>NS</td>
</tr>
<tr>
<td>NB</td>
<td>NB</td>
</tr>
</tbody>
</table>

Table 2. Fuzzy Rule Table
{  
  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.
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):

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

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 $[x_{k-1}, x_k]_{k=1}$
- $h = \frac{t_1 - t_0}{m}$

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.

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 stage is the boost converter in order to boost the voltage to the load.
- The third stage is the DC motor in order to drive 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 are 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](image)

![Figure 14. Optimized Membership Function of Change of Error Δε](image)

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.
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 to 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
A PSO-based Optimization of a Fuzzy-based MPPT Controller for a Photovoltaic Pumping System

Figure 20. Variation of the Motopump Speed

Figure 21. Variation of the Water Flow Rate

Figure 22. Progress of the Tank Volume
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 ($\approx 253W$), with the power in Figure 19 between 25s and 37s, in some conditions.

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>P&amp;O</th>
<th>FL</th>
<th>FL-PSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (W)</td>
<td>$9.0577e^3$</td>
<td>$9.2708e^3$</td>
<td>$9.6700e^3$</td>
</tr>
<tr>
<td>Flow (m$^3$/h)</td>
<td>115.1771</td>
<td>118.3621</td>
<td>124.2823</td>
</tr>
<tr>
<td>Volume (m$^3$)</td>
<td>0.8955</td>
<td>0.9584</td>
<td>1.0021</td>
</tr>
</tbody>
</table>

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:

  \[
  \begin{bmatrix}
  40.7547 & 3.2365 & 3.2821 \\
  45.2990 & 19.4148 & 0.1882 \\
  6.4366 & 19.1476 & 4.2472 \\
  45.6775 & 9.7590 & 4.6706 \\
  31.6547 & 16.0256 & 3.5969 \\
  4.9673 & 2.9235 & 3.7911 \\
  13.9971 & 8.4930 & 3.7182 \\
  27.3984 & 18.3231 & 1.9672 \\
  47.8796 & 15.8649 & 3.2808 \\
  48.2479 & 19.1939 & 0.8642 \\
  \end{bmatrix}
  \]

- Best swarm matrix:

  \[
  \begin{bmatrix}
  37.5882 & 16.8303 & 1.7648 \\
  12.8292 & 5.1692 & 4.1558 \\
  25.3473 & 16.3043 & 2.9305 \\
  34.9839 & 4.9461 & 2.7531 \\
  44.5961 & 18.5023 & 4.5868 \\
  47.9686 & 7.0647 & 1.4363 \\
  27.4061 & 4.0122 & 3.7584 \\
  7.0174 & 5.0966 & 3.7711 \\
  \end{bmatrix}
  \]

- Best particle 9th in Best swarm matrix :

  \[
  [7.5498, 12.3593, 1.9084] 
  \]

- Simulation time : 11827s.
REFERENCES


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A PSO-based optimization of a fuzzy-based MPPT controller for a photovoltaic pumping system used for irrigation of greenhouses is presented. The paper discusses the implementation of a PSO-based MPPT controller in a photovoltaic pumping system for irrigation of greenhouses in Layhouat, Algeria. The controller is designed to maximize the efficiency of the photovoltaic system by operating at the maximum power point (MPP) under varying environmental conditions.

The PSO algorithm is used to optimize the controller parameters in order to achieve better performance. The results show that the proposed PSO-based MPPT controller outperforms the conventional Perturb and Observe (P&O) method in terms of tracking speed and steady-state error. The proposed controller also provides better performance under partial shading conditions, which is a common issue in photovoltaic systems.

The study concludes that the PSO-based MPPT controller is a viable solution for improving the efficiency of photovoltaic pumping systems used for irrigation in greenhouses.

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