Implementation of Photovoltaic Maximum Power Point Tracking Fuzzy Logic Controller on FPGA

Hanen Abbes¹, Kais Loukil¹, Hafedh Abid², Mohamed Abid¹, Ahmad Toumi²

¹ Laboratory of Computer and Embedded Systems (Lab-CES)
hanenabbes2009@yahoo.fr

² Laboratory of Sciences and Techniques of Automatic control & computer engineering (Lab-STA)

Abstract: In order to enhance the efficiency of the photovoltaic system, a technique called Maximum Power Point Tracking (MPPT) is substantially used. It allows photovoltaic panel operates at its maximum output power. Fuzzy logic technique seems to be an auspicious solution that ensures optimal operation of photovoltaic system. It is a fashionable, flexible and robust technique.

Therefore, due to the photovoltaic system complexity and their specific behavior, one solution consists to adapt FPGA technology to prototype and test photovoltaic system. This paper presents the control of photovoltaic system using a new fuzzy logic technique to track the MPP then its implementation on FPGA technology. Results of prototyping show an efficient system in terms of the control and performances.

Keywords: Photovoltaic; MPP; controller; Fuzzy Logic; design; FPGA.

I. Introduction

Renewable energy technologies are enormously progressed to meet the increase of the electricity demands. As a kind of free, inexhaustible and clean energy, solar energy is widely used. With 38.7 GW installed globally last year, capacity of solar PV has reached 177 GW worldwide. About 50 GW of new capacity additions worldwide is predicted, in the next years, capacity is expected to twice [1, 2].

Solar collection power process depends on many factors. The main factors that affect the system efficiency are: solar cell efficiency, radiation intensity and storage techniques. Solar cell efficiency depends chiefly on cell techniques. Commercial versions of such cells are currently around 22% efficient at converting sunlight into electric power. Then, a very small improvement in that number can significantly increase total output power [3].

PV energy production is nonlinear. Indeed, photovoltaic cell has a nonlinear characteristic and there is only one operating point where PV cell delivers its maximum of energy. This point position is not static but changes according to the irradiation and temperature variations. Maximum power point (MPP) tracking is an essential technique that tracks the optimal point and therefore increases power output. In the literature, numerous techniques have been made to have continuous maximum power [4, 5]. These techniques are marked by simplicity, popularity, accuracy, reliability, quickness, cost and others [6, 7, 8]. We mentioned namely Hill Climbing, Perturb and Observe, Incremental Conductance, short circuit current, open circuit voltage, fuzzy logic and neural network technique.

Most of researchers deal with Perturb and Observe and Incremental conductance techniques to control PV system. These techniques are popular, simple and easy to implement. The basic idea is to change slightly the operating voltage of the PV panel then observe the output power. If the power increases, the perturbation should be kept at the same direction, else, it should be reversed. However, since this principle relies on fixed step to get optimal power, some drawbacks occur such as oscillations around the MPP and slow converging to the optimal point. Several techniques have been proposed to overcome classical techniques drawbacks [9]. Mamdani type fuzzy logic controller has usually been applied to control systems. Fuzzy theory made up of fuzzy sets and linguistic rules has been investigated to offer new performances. Since fuzzy logic is conceptually easy to understand and it is powerful technique, the number and variety of applications of fuzzy logic have greatly increased [10]. The advantage of the fuzzy logic technique compared to classical ones is that it does not exactly require any mathematical model of the plant. It relies on system operator experience and it handles system nonlinearity. The impressive thing of the fuzzy logic control is that the
linguistic system definition becomes the control algorithm [11]. In this work, a Takagi-Sugeno type fuzzy system is used to control PV panel. Indeed, a new fuzzy MPPT controller is considered to follow the MPP in order to ensure an efficient system operation.

The numeric achievements of MPPT controllers’ implementation have been commonly carried out using microcontrollers and digital signal processors (DSP) [12, 13]. DSP-based controllers are generally appropriate for controllers requiring larger data size and heavier mathematical calculations. DSP devices provide reasonable benefits, but it can’t offer performances that hardware solutions can potentially give to the MPPT controller. FPGA-based controllers are suitable to algorithms deal with parallel operation. This HW solution achieves shorten development time and cost less. In addition to the robustness, FPGA circuit is characterized by the expandability that is able to expand an FPGA-based MPPT control system to treat multi-channel control.

Basil M. in [14] proves that FPGA technology is a key solution which is able to operate faster than a microcontroller. FPGAs offer also lower cost since various electronic functions required by the control unit can be integrated into the same FPGA chip.

Due to the facts that time-to-market challenge has raised the need for shortening the development process, new techniques and methodologies are introduced. In today’s, verification phase in design process has become an interesting technique and a major part, not only because it is time consuming but also owing to the increasing complexity in both Hardware and Software.

Hence, in order to reach system verification and early detection of system errors, Hardware-In-the-Loop simulation method (HILS) is widely used [15, 16]. HILS systems have facilitated development in numerous fields, including automotive engineering, aerospace, power systems, manufacturing and robotics [17]. In fact, it is an efficient solution that enables you tests your embedded system before deploying it in production environment. It allows a whole simulation of the system while some of its functions are implemented on FPGA hardware solution. Thanks to these advantages, this method is used to perform the verification task to our photovoltaic system.

Consequently, to improve output efficiency of the photovoltaic system, it is absolutely necessary to: first have a reliable maximum power point tracking technique, second, design the MPPT controller for PV system while using FPGA circuit, it is a vital requirement to get the best speed/cost ratio.

So, the main contribution of this work is to design then implement a fuzzy logic MPPT controller for a PV system on FPGA device as is developed in [29].

Figure 1. Block schema of photovoltaic system

A. Photovoltaic panel

A photovoltaic system employs solar panels which are composed of a number of solar cells to supply usable solar power.

The photovoltaic cell is the basic component of photovoltaic panel. A module is an assembly of PV cells. A panel unit is a several modules assembled into a single structure. A great number of panels electrically connected in series constitute an array. Numerous arrays electrically connected in parallel form the generator or photovoltaic field. As a result, PV generator is able to generate the required power.

Figure 2. Photovoltaic cell, panel and array
An electrical model is indispensable to study the photovoltaic cell operation. In the literature, many models have been developed to represent their nonlinear behavior, namely the model based on one diode and the model based on two diodes.

The single diode model is more convenient in PV model since it requires less complex equations [18, 19]. A typical single diode equivalent circuit for PV cell is shown in Fig. 3. The $I_{sh}$ current is the current source which is proportional to light incident. The $I_d$ current is the diode current of the PN junction of the PV cell. Voltage losses and leakage currents are modeled by series resistance ($R_s$) and shunt resistance ($R_{sh}$).

**Figure 3.** Equivalent electric circuit for PV cell

Equations arising from this equivalent model are given by the following ones.

According to Kirchhoff’s law, the photovoltaic current delivered from the PV cell is equal to:

$$I_{PV} = I_{sc} - I_d - I_{sh}$$  \hspace{1cm} (1)

The current generated by photovoltaic cell has $I_{sc}$ expression given by equation 2.

$$I_{sc} = (I_{cc} + K_F(T - T_{ref})) \frac{G}{G_n}$$  \hspace{1cm} (2)

The current $I_d$ expression of PN junction is given by:

$$I_d = I_s \left[ \exp \left( \frac{V_{PV} + R_s I_{PV}}{nV_T} \right) - 1 \right]$$  \hspace{1cm} (3)

The current flowing in $R_{sh}$ resistance is equal to:

$$I_{sh} = \frac{V_{PV} + R_s I_{PV}}{R_{sh}}$$  \hspace{1cm} (4)

Where:
- $I_c$: Short circuit current.
- $D$: Diode representing the PN junction.
- $T$: Temperature

$T_{ref}$: Reference Temperature ($25^\circ$C).

$G$: Irradiation.

$G_n$: Reference irradiation (1000 W/m²).

Electrical characteristics of photovoltaic cell Current-Voltage (I-V) and Power-Voltage (P-V) are illustrated by Fig. 4. It is very clear that these characteristics have nonlinear behavior with a single point where the PV power is maximum.

This point varies with irradiation and temperature changes. So, it is crucial to control DC-DC converter switch periodically via MPPT controller to have optimal energy of PV panel.

**Figure 4.** P-V curves of photovoltaic cell under temperature variations.

**Figure 5.** P-V curves of photovoltaic cell under irradiation variations.

Fig. 4 shows the evolution of the P-V characteristic for a PV panel under different values of temperature at constant irradiation. We note that the power generated by the PV panel increases when the temperature decreases. In addition, similar to the power, the voltage giving the maximum power increases when the temperature decreases.

Fig. 5 shows the evolution of the P-V curve for PV panel under irradiation variations at constant temperature. We note that PV power increases when irradiation increases. In
addition, the voltage giving the maximum power decreases slightly when the irradiation increases.

B. MPPT fuzzy controller

1) T-S Fuzzy model

A T-S fuzzy logic system is generally applied to non-linear system. Its principle operating is shown in Fig. 6.

![Fuzzy logic system diagram](image)

**Figure 6. T-S fuzzy model schema diagram principle**

The fuzzy system is a set of fuzzy IF-THEN rules [20]. The rule form is written as follows:

\[
\text{IF } z_1(t) \text{ is } M_{i1} \text{ AND } \ldots \text{ AND } z_p(t) \text{ is } M_{ip} \text{ THEN } y_1 = \frac{y_1^i}{\sum_{i=1}^{c} w_i(z(t))}, i=1, 2, \ldots, c
\]

Here,

- \(M_{ij}\) is the fuzzy set and \(c\) is the number of model rules,
- \(y(t)\) is the output vector and \(z_1(t), \ldots, z_p(t)\) are premise variables.

For each rule \(R_i\) is attributed a weight \(w_i(z(t))\) which depends on grade of membership function of premise variables.

\[
w_i(z(t)) = \prod_{j=1}^{p} \mu_{M_{ij}}(z_j(t))
\]

The term \(\mu_{M_{ij}}(z_j(t))\) is the grade of membership of \(z_j(t)\) in \(M_{ij}\).

Weighting functions \(w_i\) should be normalized as:

\[
\frac{w_i(z(t))}{\sum_{i=1}^{c} w_i(z(t))}
\]

Where,

\[
\sum_{i=1}^{c} w_i(z(t)) > 0
\]

\[
w_i(z(t)) \geq 0
\]

And,

\[
\sum_{i=1}^{c} h_i(z(t)) = 1
\]

\[
h_i(z(t)) \geq 0
\]

The output of the fuzzy system can be written as:

\[
y_1(t) = \frac{\sum_{i=1}^{c} y_i^i w_i(z(t))}{\sum_{i=1}^{c} w_i(z(t))}
\]

2) MPPT algorithm based on T-S fuzzy logic

Maximum power point tracking technique is a fundamental item in photovoltaic system that increases the output power. Fuzzy logic is an advantageous concept which is recently used in maximum power point tracking systems. Indeed, this intelligent technique has been introduced because it deals with the non linearity of the system and it does not require an accurate mathematical model. It is applied to photovoltaic system since it is robust and a favorable technique which operates at the optimal point without oscillations [21]. Its principle relies on fuzzy sets and linguistic rules. Fuzzy logic controller as elaborated in [22] operates in two basic stages: fuzzification stage and inference engine stage. The first fuzzification stage target is to convert numerical input variables into linguistic variables. In the second stage, a rule inference table is made while considering Sugeno inference method, to provide finally a concrete output value.

The error \(E\) and the change of the error \(CE\) are the two inputs of fuzzy logic system. Their expressions are described by equations (7) and (8):

\[
E = \frac{i}{v} + \frac{di}{dv}
\]

And,

\[
CE = E(k) - E(k - 1)
\]

Each input is described by five linguistic sets: Negative Small (NS), Positive Big (PB), Zero (Z), Positive Small (PS), and Negative Big value (NB). Membership functions of the two inputs are drawn in Fig. 7.
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**Figure 7.** E (A) and CE (B) membership functions

**Table I. Inference rule table**

<table>
<thead>
<tr>
<th>E</th>
<th>NB</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>B</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>B</td>
</tr>
<tr>
<td>NS</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>B</td>
</tr>
<tr>
<td>Z</td>
<td>B</td>
<td>S</td>
<td>M</td>
<td>S</td>
<td>M</td>
</tr>
<tr>
<td>PS</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>PB</td>
<td>S</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>B</td>
</tr>
</tbody>
</table>

Table 1 summarizes fuzzy rules. The concrete output is the duty cycle variable step which can be Small (S), Medium (M) or Big (B).

Twenty five rules are elaborated using the concept of incremental conductance algorithm. To better understand, we explain an example of a control rule: If (E1 is NB) and (E2 is NB) then (step is B); It means that if the slope has a huge value and the change of the slope is also big, therefore the operating point is far from the MPP and we should set a big step value.

### III. Photovoltaic system Design and prototyping

#### A. FPGA technology

**FPGA:** Field Programmable Gate Array is a programmable digital integrated circuit that can be configured to carry out any digital function. It has emerged as platform of choice for efficient hardware realization of computation intensive algorithms because of their intrinsic parallelism and flexible architecture. The two main technologies which distinguish FPGAs are architecture and the computer-aided design (CAD) tools that user may apply to have FPGA designs [23]. FPGA device is widely used to prototype, test and to control power electronic systems [24, 25]. To have an efficient FPGA implementation, a typical FPGA design flow, as given in Fig. 8, is followed: First, the system is encoded at very high level: HDL or schematic entry, depending on the complexity of the system. The VHDL language: Very High Hardware Description Language is used to program this device. Second, a synthesis step is done, and then a NetList form is generated. Third, the place and route step places the sub-blocks into logic blocks according to the constraints and connects the logic blocks. Finally, to configure FPGA circuit, a bit-stream form is substantial for device programming. Verification task is carried at different stages of the process flow.

**Figure 8.** FPGA design flow

**B. Simulation of photovoltaic system using co-simulation tool**

System design process includes verification step that aims to ensure an effective system operation. To fulfill this verification task, co-simulation tools are used. In fact, it is more efficient when the simulation platform is reliable, flexible to change, accurate and with minimum risk of fault. The integration of target architecture in the simulation loop, known as Hardware-In-the-Loop (HIL) method, has the advantage to provide realistic verification and therefore improves the test quality [26]. Hardware-In-The-Loop method allows simulation of the entire system on a computer by the means of Matlab-Simulink tool while some of its functions is developed with DSP-Building tool as a real hardware platform. Hence, real-time HIL simulation method substitutes the emulated hardware under test and enables examining critical situations. This reduces risks of arising errors in last stages of the test system and consequently minimizes the gap between design and implementation. The main steps of the HIL simulation method are: first, develop a mathematical model. Second, test your device on a simulated...
process. Finally, implement your HW on the real process [27].

This method principle as illustrated by Fig. 9 is applied to test the operation efficiency of the photovoltaic system.

![Figure 9](image_url)

**Figure 9.** The principle of the Hardware-In-the-Loop simulation method

Experimental results, as shown in Fig. 10, prove that photovoltaic output power obtained after applying HILS method are closely matched with results of the complete PV system modeled on Matlab-Simulink software. Therefore, these results show that photovoltaic system operates properly at its optimal power.

![Figure 10](image_url)

**Figure 10.** Optimal output power of photovoltaic system when performing HIL simulation method

IV. Implementation of the fuzzy logic technique on FPGA circuit

A. **MPPT fuzzy controller design on FPGA circuit**

FPGA circuit is mainly made up of Configurable Logic Blocks (CLBs) connected via a programmable network. Each CLB structure regroups a number of logic units called slices. The slice unit includes a number of look-up tables (LUTs) and registers. The main goal in design and implementation process is to have optimized hardware architecture with a minimum number of CLBs [28]. To implement Fuzzy Logic Controller (FLC), each component of the fuzzy system is encoded using VHDL language integrated in Altera QUARTUS 13.0 tool. It is a standard language and its description is independent from technology. In spite of the fact that the design of the fuzzy logic technique is complex, this technique is highly flexible. In fact, membership functions and the rule base can be smoothly modified by easily changing some parameters and design constraints.

The implementation of a fuzzy technique using FPGA generally requires a great number of logic gates. To process on tracking the MPP of the PV system, the fuzzy system structure includes seven main control blocks as shown in Fig. 8: the $I_{pv}$ and $V_{pv}$ inputs acquisition, fuzzification, inference engine, determining sign direction, duty ratio generation and PWM generation block. The control system receives voltage and current values, computes all necessary inputs for fuzzification block and selects the rules to compute membership values. Finally, giving the sign direction and the decision based on weight average, the MPPT controller provides the new duty ratio output value.

![Figure 11](image_url)

**Figure 11.** Fuzzy logic MPPT controller inside FPGA

**Fuzzification unit:**

The first task in the MPPT fuzzy controller is the fuzzification unit which converts crisp inputs into fuzzy terms sets. We rely on arithmetic approach to compute $E_1$ and $E_2$ inputs of the fuzzification unit. Then, the membership degrees are computed while using a membership function as given this following code.

```vhdl
function belonging (x, a, b, c, d: integer) return integer is
  variable dom : integer := 0;
begin
  if ((x > a) and (x < b)) then
    dom := (x-a) * (b-x);
  elsif ((x < c) and (x > d)) then
    dom := (d-x) / (d-c);
  elsif ((x > b) and (x < c)) then
    dom := 1;
  else
    dom := 0;
  end if;
return dom;
end belonging;
```
The implementation of the fuzzification unit is carried out as given in Fig. 12. For each input, the membership degrees are computed.

![Figure 12. Fuzzification unit implementation on FPGA device](image)

**Inference engine:**

As we have two inputs and five membership sets describing E1 and E2 inputs, we get as result $2^5$ rules. So, the fuzzy rule system includes 25 sub rules according to the range of the inputs. First, a rule checker selects only the active rules for the current inputs E1 and E2. Then, concrete values of membership functions are provided to the decision block based on weighted average method to produce finally the output value of the duty ratio variable size. This mechanism is depicted by Fig. 13.

![Figure 13. Inference unit implementation on FPGA device](image)

**B. MPPT fuzzy controller process**

The use of a DC-DC converter is necessary to maintain PV output voltage at its optimal value. PV system composed of PV panel, Boost converter and the load has as inputs the voltage and current variables of the solar panel. The crisp output of the controller is the duty cycle of the pulse width modulation which controls the DC-DC converter switch. The block diagram of the Maximum power point tracking (MPPT) system is given by Fig. 14.

![Figure 14. Model schema of the PV Maximum power point Tracking system](image)

At each sample time, the conductance ($I/V$) and the change in the current relative to the voltage ($dI/dV$) are computed. Therefore, the first input of the fuzzy MPPT controller E1 which is equal to the sum of the ($I/V$) and the ($dI/dV$) is determined. After that, the second input E2 determined by $E1(k) - E1(k-1)$ relation is computed. The output of this fuzzy logic-based new algorithm is the variable step of the duty cycle which is determined according to the slope value of Power-Voltage characteristic for photovoltaic panel. In the final step, a concrete variable step value is provided to the duty ratio generation block to have the appropriate value of duty cycle.

**C. MPPT fuzzy controller implementation**

Cyclone II 2C35 FPGA board is used for the realization as shown in Fig. 15.

![Figure 15. FPGA board used for MPPT controller](image)

This FPGA chip is chosen to implement the MPPT fuzzy logic controller designed above since it presents an optimal architecture dedicated for high density and high performance logic design. Given the reports obtained from the implementation process, the slices number is 17480; the 4-input LUTs number is 17389; the percentage of FPGA occupation is 53%. The maximum operating frequency is 100
MHz. Table 2 summarizes the device utilization for the MPPT controller process implemented on FPGA device.

**TABLE II. FPGA utilization ratio for fuzzy-based MPPT controller**

<table>
<thead>
<tr>
<th>Items</th>
<th>Total number</th>
<th>Slices</th>
<th>Utilization ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slices</td>
<td>33216</td>
<td>17480</td>
<td>53%</td>
</tr>
<tr>
<td>Registers</td>
<td>33216</td>
<td>332.16</td>
<td>1%</td>
</tr>
<tr>
<td>LUTs</td>
<td>48</td>
<td>17389</td>
<td>52%</td>
</tr>
<tr>
<td>RAMs</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pins</td>
<td>475</td>
<td>97</td>
<td>20%</td>
</tr>
</tbody>
</table>

The VHDL block diagram of the fuzzy MPPT technique is illustrated by Fig. 16.

**Figure 16. Block/schematic diagram of the fuzzy MPPT technique**

The RTL schematic diagram of the proposed MPPT controller is given by Fig. 17.

**Figure 17. RTL schematic diagram of the fuzzy MPPT technique**

Test bench values, Ipv current input and Vpv voltage input values, are processed to test the operation of the MPPT algorithm. The duty ratio ‘d’ is the output value. For each high clock cycle state, the voltage and current values are sent to the MPPT controller, they are processed in order to compute the duty ratio variable step, then the direction of tracking is determined and finally the new duty ratio is provided. The functional simulation of the MPPT technique is depicted by Fig. 18.

**Figure 18. Simulation results of the photovoltaic system based-on fuzzy MPPT controller**

**Conclusion**

In this paper, a fuzzy logic MPPT technique is designed and implemented on FPGA circuit in order to control photovoltaic system. Since an efficient maximum power point tracking technique is a vital item that increases the PV output power, a new fuzzy logic technique is used to control PV system. The FPGA device is chosen as a powerful and efficient tool in terms of computing power and parallelism to implement the fuzzy MPPT technique. Simulation results exhibit important advantages of the target method such as the ability to track the MPP within a short time and without oscillations and thus an efficient operation of photovoltaic system. To highly increase PV output power, it is very interesting in the next step to investigate FPGA technology to control photovoltaic multi-channel system.

**References**

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