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# FPGA-based implementation of a fuzzy controller (MPPT) for photovoltaic module

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ABSTRACT

This paper describes the hardware implementation of a two-inputs one-output digital Fuzzy Logic Controller (FLC) on a Xilinx reconfigurable Field-Programmable Gate Array (FPGA) using VHDL Hardware Description Language. The FLC is designed for seeking the maximum power point deliverable by a photovoltaic module using the measures of the photovoltaic current and voltage. The simulation results obtained with ModelSim Xilinx Edition-III show a satisfactory performance with a good agreement between the expected and the obtained values.



## 1. Introduction

Tracking the maximum power point of a photovoltaic (PV) array is an essential task in a PV control system because it maximizes the power output of the PV system for a given set of conditions, and therefore maximizes the array efficiency. Consequently, various efficient MPPT (Maximum Power Point Tracking) techniques have been developed and proposed in literature [1]. The most used tracking techniques are: the Perturb and Observe (P&O) methods, the constant voltage method, the short-current pulse method, the Artificial Neural Network (ANN) method, the fuzzy logic (FL) method, and etc. [2–4]. The Fuzzy Logic Controller (FLC) based method performs well under varying climate conditions (cell temperature and irradiance) [4]. In this context, effort has been concentrated on the development of software as a yet simple and cost effective solution [5]. More recently, a considerable interest in the development of the FLC hardware implementations has been shown [6]. This yields to high speed processing and permits the integration of such MPP tracker on relatively small-embedded systems. However, the main drawback of this approach is that it is only cost effective for high volume applications. A more feasible methodology for lower volume applications requires the use of general purpose or programmable hardware such as the FPGAs chips. The MPPT has been already implemented in microcontrollers [7] and digital signal processors (DSPs) [8]. While DSPs can provide a reasonable performance, they do not provide the advantages that field-programmable gate arrays (FPGA) chips can potentially offer to the implementation of MPPT control [9]. In comparison to DSP implementations, FPGAs offer lower cost implementations since the functions of various components can be integrated into the same FPGA chip [10]. In addition, FPGAs can provide equivalent or higher performance with the customization potential of an ASIC. As FPGAs can be reprogrammed at any time, repairs can be performed in situ while the system is running thus providing a high degree of robustness. Beside robustness, this reprogrammability can provide a high level of (i) flexibility that allows simple upgrading of the MPPT control system by merely updating or modifying the MPPT algorithm running on the FPGA chip, and (ii) expandability that makes expanding an FPGA-based MPPT control system to handle multi-channel control. In addition, by allowing the emulation of the entire MPPT control system onto the FPGA chip, this reprogrammability provides a level of testability that DSPs cannot match. Owing to these characteristics, the FPGA seems to possess a great potential for the use in the solar energy field. For this reason, this circuit has been chosen in order to achieve the hardware implementation of an MPPT Fuzzy Logic Controller. The implemented FLC is partitioned into many independent functional modules.

The rest of the paper is organized as follows. In the next section, a brief description of the considered MPPT system's architecture is

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**Nomenclature**

| | |
|---|---|
| *ANN* | Artificial Neural Network |
| *ASIC* | Application Specific Integrated Circuit |
| *COG* | Center of Gravity |
| *DSP* | digital signal processor |
| *D* | the duty cycle ratio |
| *DC/DC* | DC to DC Converter |
| *E, ΔE* | Error and Change in Error |
| *FLC* | Fuzzy Logic Controller |
| *FPGA* | Field-Programmable Gate Array |
| *G* | Solar Irradiation ($W/m^2$) |
| $I_m$ | measured current (A) |
| *MPPT* | Maximum Power Point Tracking |
| *MOSFET* | Metal-Oxide Semiconductor Field-Effect Transistor |
| *P&O* | Perturb and Observe |
| $P_{max}$ | maximum power (W) |
| *PV* | photovoltaic |
| *PWM* | Pulse Width Modulation |
| *RTL* | Register Transfer Level |
| *T* | temperature (°C) |
| *VHDL* | very high speed Hardware Description Language |
| $V_m$ | measured voltage (V) |
| $V_{max}$ | maximum voltage (V) |
| $V_o$ | output voltage (V) |

explained. Section 3 describes the hardware implementation of the FLC. Simulations results and the test of the proposed FLC are addressed in Section 4. Section 5 emphasizes the hardware implementation on Virtex II (XC2v1000) FPGA from Xilinx. Finally, conclusions are presented in Section 6.

## 2. MPPT based fuzzy logic control technique

A typical block diagram of a generic PV controlled system is depicted in Fig. 1. It consists of a solar array, a DC/DC converter (in this case a boost converter), one or two A/D converters, an MPPT control unit, and a resistive load.

The control circuit allows to follow the Maximum Power Point (MPP) checking the actual PV module voltage $V_0$ and power $P_0$ in one switching period and driving a DC/DC converter in order to oscillate around the voltage $V_{max}$ corresponding to the actual MPP.

Fig. 2 depicts the main components of the boost DC/DC converter, which is generally used in such PV system setups. The power MOSFET is usually used as a switching device since it is easy to control and can be operated at high frequencies. The power flow is thus controlled by varying the on/off duty cycle of the switching period. The average output voltage $V_0$ is determined by the equation [2]:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \quad (1)$$

In which: $D$ is the duty cycle of the switching period.

The power-voltage characteristic of a PV module is characterized by a MPP which is unique and climate conditions dependent (irradiation and cell temperature). As an example, in Fig. 3 the MPP $P_{max}$ corresponding to an irradiance of 1000 $W/m^2$ and a cell temperature of 25 °C is shown.

The MPPT using the FLC approach is designed in a manner that the control task try continuously to move the operation point of the solar array as close as possible to the maximum power point (*MPP*) [7].

$$E(n) = \frac{p(n) - p(n-1)}{V(n) - V(n-1)} \quad (2)$$

$$\Delta E(n) = E(n) - E(n-1) \quad (3)$$

where $E$ and $\Delta E$ are the error and the change in error respectively, $n$ is the sampling time, while $p(n)$ is the instant power delivered by the PV generator; $V$ is the instant voltage.

The inputs are chosen so that the instant value of *E(n)* shown the load operation power point's direction. It is possible to know if the operating point stays in a zone where the derivative of the *P–V* characteristic is positive or negative, while Δ*E(n)* shows in

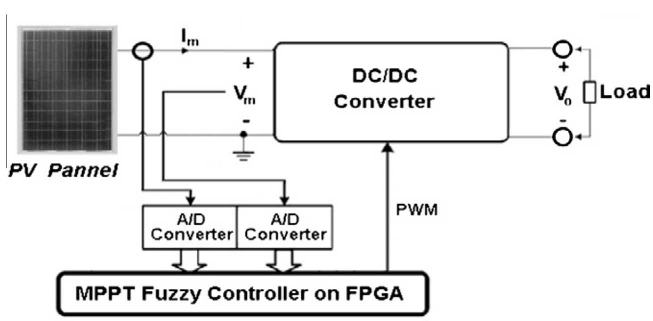


**Fig. 1.** The MPPT control system connected to a PV module.

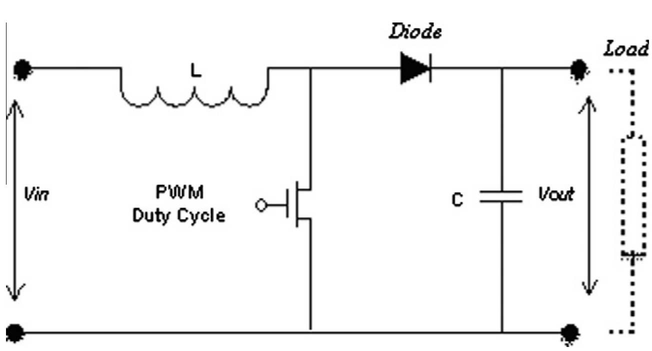


**Fig. 2.** The boost DC/DC converter.

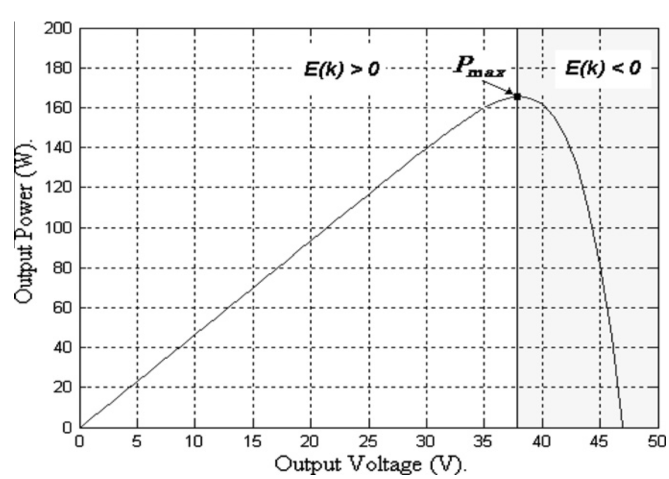


**Fig. 3.** Power-voltage characteristic at 25 °C and 1000 $W/m^2$.