Fuzzy-based MPPT algorithm implementation on FPGA chip for multi-channel photovoltaic system

Hanen Abbes[1], Hafedh Abid[2], Kais loukil[1], Mohamed Abid[1], Ahmad Toumi[2]
[1]Laboratory of Computer and Embedded Systems (Lab-CES), Department of Electrical Engineering, University of Sfax, Sfax, Tunisia
[2]Laboratory of Sciences and Techniques of Automatic control (Lab-STA), Department of Electrical Engineering, University of Sfax, Sfax, Tunisia

Article Info

Article history:

Received Oct 20, 2021
Revised Dec 2, 2021
Accepted Jan 23, 2022

Keywords:

Channels
Field programmable gate array
Fuzzy logic
Maximum power point tracking
Photovoltaic

ABSTRACT

Microprocessors and microcontrollers are mostly used to control electrical systems. These chips front into problems while monitoring systems that need heavy computing and important processing. Likewise, they fail while handling inputs and outputs speeds, especially with multi-channel photovoltaic (PV) systems. In comparison to a digital signal processor (DSP) and microcontroller implementations, field programmable gate array (FPGA) device is able to integrate a great number of PV channels and to achieve short development time, cost less and more flexible operation. As well, new control algorithms are increasingly complex; using new performing technologies is very motivating. Mainly, FPGA technology is adopted thanks to its ability to control complex applications and intelligent laws. In opposition to traditional controls, fuzzy logic based control presents more efficiency and reliability response for non-linear systems. Therefore, this paper deals with the execution of the fuzzy-based maximum power point tracking (MPPT) technique by the means of the FPGA chip for a multi-channel photovoltaic system. A multi-channel photovoltaic system is designed. Then, the FPGA circuit is investigated to get benefits from this hardware solution. Since software implementation way integrates a limited number of PV panels, hardware implementation is a promising solution that reduces execution time and therefore controls a huge number of photovoltaic channels. Finally, results of simulation of the fuzzy technique implementation on FPGA chip show that the proposed PV system controls more than 4400 channels. Therefore, the system output power is increased and the system profitability is improved.

This is an open access article under the CC BY-SA license.

Corresponding Author:

Hanen Abbes
Laboratory of Computer and Embedded Systems, Department of Electrical Engineering, University of Sfax
Road of Aeroport Km 5, Sfax, Tunisia
Email: hanenabbes2009@yahoo.fr

1. INTRODUCTION

Coupling photovoltaic sources to the electrical grid have become more motivating since the rapid rise in demands of renewable energy. Needs on clean energy will have the fastest growth in the electricity sector. Recently, photovoltaic energy is particularly used in space, transportation applications and in building-integrated photovoltaic; in which solar arrays are in the roofs of the buildings and houses [1]–[4]. Accurately, the generation of photovoltaic (PV) power is dependent on temperature degree and chiefly irradiation level. This latest is greatly tied to sunshine angle, shadings from birds, falling leaves, buildings, dusts, and clouds. In order to increase power to maximum, sun trackers and techniques of tracking maximum power point are largely applied for PV arrays [5], [6]. Earlier, numberless maximum power point tracking techniques has been deployed and put in practice [7]–[10]. The rinciple of this control technique relies on varying the duty ratio until an optimal value is reached. Therefore, the amount of power delivered by the PV panel attains its maximal value. Numerous methods caught from the literature dating back to the first techniques are discussed in [11]. Traditional techniques are more suitable to be implemented by dint of their simple structure and their reduced calculations. Recently, the fuzzy logic concept is exploited to control electrical systems. Instead of conventional techniques, fuzzy logic control is evaluated as a fashionable technique and an auspicious solution to non-linear systems tuning. It is an effective technique since it converges rapidly to optimal power [12]–[14]. It is driven by its smallest oscillations in steady state and good response under rapid irradiation changes [15], [16]. However, this technique is complex.

To integrate PV energies sources to DC grid (batteries of electrical vehicles) or to AC utility grids, many photovoltaic system configurations exist [17], [18]. PV distributed system configuration is deeply used since it acts as an essential part of the electrical grid [19]. It plays a substantial role as a power supply ressource. It is a huge park including multiple channels of PV panels which are parallel connected and each PV panel is linked to AC or DC grid through AC-DC or DC-DC converter [20], [21]. In this system, a local control item is generally introduced to each PV source conversion stage. Each PV source operates at its own maximum power point. Moreover, a centralized control unit is necessary for the entire system monitoring, power supervision and protection. This conventionnel system seems to be congested and needs a great number of electronic power devices.

The great technological challenge which arises with integrating multi-channel photovoltaic systems is the system control. Early, microcontrollers are used for simple systems and classical applications especially for some photovoltaic systems [22]–[24]. Nevertheless, this type of implementation confronts a serious problem: it does not support a sizeable application. Indeed, it does not allow excellent performance: the frequency and the area are relatively limited. In general, it is unable to handle complex applications and in particular to implement intelligent control laws. With the emergence of new performing algorithms and intelligent laws, new target technologies are substantially required. Thus, digital signal processors (DSPs) and field programmable gate arrays (FPGAs) seem to be the key solutions [25], [26]. Mostly, DSP-based systems are very appropriate in case of large data size and heave mathematical calculations of control technique. FPGA-based systems are more suitable to control technique which requiring parallel performing. Indeed, DSP are exploited for finding and tracking the optimal point of PV panels as in [27], [28]. Overall, this circuit is broadly used. However, C compilers are often inefficient because of the heterogeneous architecture of the DSP circuit which then forces designers to code the application into assembly language. However, it is tedious work and requires a significant development time (time-to-market). Furthermore, the computing power of DSPs is widely exceeded by smashing the sequential executing pattern and attaining more cycles per clock. In fact, designers of embedded and high-quality performance systems are blessed with new opportunities and challenges for designing applications using FPGA-based hardware platforms [29]. In particular, the use of intelligent and complex maximum power point tracking (MPPT) control algorithms incites researchers to use FPGA.

So, the proposed solution is to use an FPGA chip for our system. Besides robustness, FPGA provides a reconfiguration feature that allows upgrading control system easily by changing algorithm while it runs on the FPGA. Expandability feature enables to expand FPGA-based control system treat multi-channel system. Thereby, instead of multiple local control units, the FPGA device is qualified as a single central unit that prototypes the system before its practical application [30], [31]. FPGAs are advantageous circuits for controlling the PV system owing to the fast computing, low consumption and parallel architectures. So, the major contribution is to adopt an FPGA chip for searching and following maximum power point of multi-channel photovoltaic system and to harness its pertinent features to increase maximum power and system efficiency. New Arduino devices which act as microcontroller are used for comparison results. Results of implementation are given to prove the efficiency of an FPGA-based system to control multiple PV channels.

The remainder of this paper is structured as described along these lines: in section 2, a photovoltaic system and a new fuzzy MPPT controller are explained. In section 3, FPGA technology is investigated and the corresponding target method is described. In section 4, PV system carrying out is detailed then simulation results are given and discussed. The conclusion is drawn in the final section.

2. NEW MPPT METHOD FOR PV SYSTEM

2.1. PV system

Generally, there are two main configurations of PV systems: centralized and distributed. Output power generation of the traditional centralized PV system was decreased due to multiple reasons. Indeed, the whole power gotten from the string of PV panels is influenced by a part of panels in the PV system which undergoes partial shading. The components of the centralized PV system arrangement, presented in Figure 1, are a PV panel, static converter, power inverter, and control unit.

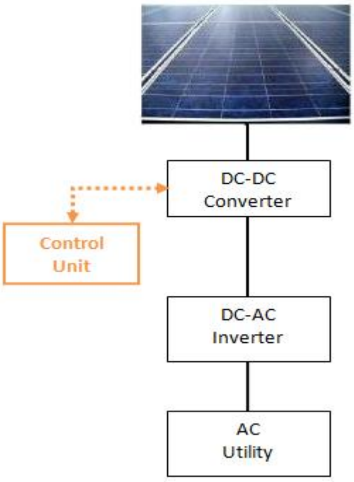

Figure 1. Central PV system configuration

The distributed PV system includes multi photovoltaic channels, DC-DC converters, control unit, AC and/or DC load. Each panel level MPPT operation and voltage measurement are parallel carried out. Every DC-DC converter requires electrical sensors to measure voltage and current values and Inputs/Outputs ports for tracking target. Each of these DC-DC converters is controlled by a distributed maximum power point tracking (DMPPT) block. This system type allows harvest energy from each panel. It overcomes the common problems of the centralized PV system and increases total energy efficiency [32]. Abbes *et al.* [33] present the implementation on FPGA of MPPT control for a simple photovoltaic system. This study focuses on distributed PV system. As drawn in Figure 2, each photovoltaic panel is supervised by MPPT item by the means of a boost converter. Indeed, a DMPPT block is directly linked to a boost converter to get the optimal operating point. As a DC-DC converter is related to only one PV panel of the photovoltaic panels set, each panel in this architecture kind has to operate at its own maximum power point.

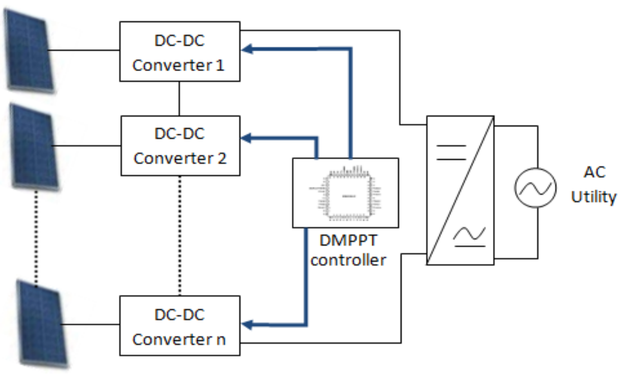

Figure 2. Multi-channel PV system

2.2. Fuzzy MPPT method

Most researchers use traditional MPPT methods to control PV system. These methods are used owing to their simple and easy implementation. Nonetheless, since these methods rely on a fixed step to get optimal power, there are some weakness: slowly converging to maximum power point, significant oscillations around this point and wrong response under rapid irradiation changes. Fuzzy concept expressed by the fuzzy sets theory and linguistic rules has been used to offer innovative efficient performances over the traditional controllers [34]. This concept has been applied since it handles the non linearity and it does not need a rigorous mathematical model. An improved MPPT technique proposed in [35] aims to overcome the drawbacks of classical techniques and to take advantage of fuzzy logic concept.

Its principle is based on three stages: i) Fuzzification; ii) Inference engine; and iii) Defuzzification. Fuzzification's end is to convert numerical input variables to linguistic variables. Then, during inference engine stage, rule inference table is made: logic relationships are defined to link inputs with outputs. Finally, defuzzification stage aims to convert linguistic variable to a concrete value. Therefore, proposed approach purpose accelerates tracking maximum power without oscillations. The idea is to use a variable step in place of a fixed step: incrementing step is big at the first, medium in the middle of the process and has a small size in the steady state. This variable step is given by a fuzzy logic block. The proposed algorithm operates as follows: At the beginning, I (k) and V (k) are computed and provided to the fuzzification stage. Then, linguistic output variables are carried out in inference stage to have decisions. dD is the variable step coming from the fuzzy block. Hence, giving the sign of dP/dV, the whole value of the duty ratio D is finally determined. The flowchart of new fuzzy MPPT is given in Figure 3.

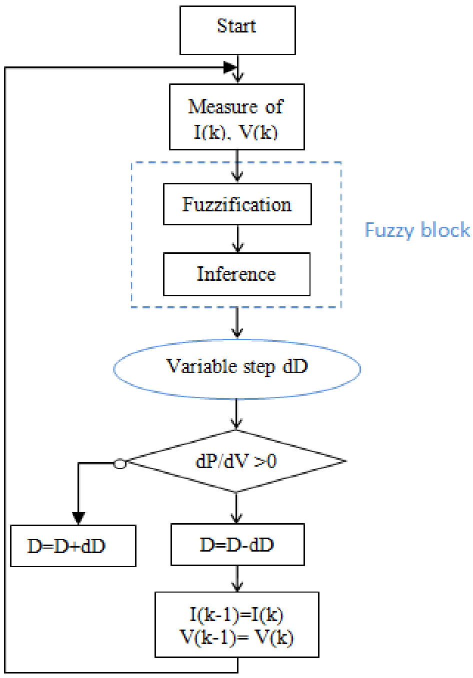

Figure 3. Flowchart of new fuzzy MPPT algorithm

3. FPGA CHIP FOR PHOTOVOLTAIC SYSTEM

Due to the increasingly progress in FPGA technology and the availability of advanced tools, application fields of FPGAs increase at a great rate and it is expected that in the upcoming years this seductive technology may even replace application specific integrated circuit (ASIC) [36], [37]. FPGAs application areas are many and various. Broadly speaking, FPGAs are present in: video processing, control systems engineering, bioinformatics, software defined radio, aerospace, astronomy, defense systems, recognition systems, medical imaging, computer hardware (HW) emulation, prototyping of ASIC, reconfigurable computing and others.

3.1. FPGA technology

In recent years, FPGAs have been arousing growing interest. This device is particularly gainful for applications based on digital control. FPGAs global market is expanding at a hugely high rate and day by day, FPGAs popularity is also growing. FPGA chip is driven by its flexibility, hardware-timed speed and reliability, and parallelism. Giving its particular architecture, FPGAs are convenient for applications and implementation of algorithms featured by parallel processing.

FPGA based systems controllers provide quite advantages that bring high performances in real time systems. Very important advantages are the speed and the low power consumption. In fact, systems using FPGA allow less execution time thanks to its hardware architecture. Besides these benefits, FPGA is a small chip with a low cost with regards to other platforms. In addition, algorithms are designed on a reconfigurable platform that can be updated or rectified easily.

3.2. FPGA Platform

A variety of alternatives are available to firms which put in place FPGA-based applications. Though numerous alternatives seem similar as the same FPGA item is produced, namely by Intel or Xilinx firm. It goes without saying that, there are many major dissimilarities between platforms. These dissimilarities can have a notable impact onto some factors such as the physical area, the power and cooling they need to continuous basis and the amount of internal resources which are primordial to deploy, monitor and support them.

To select the best type of platform for your business, it is essential to have into consideration the integration costs, the amount of continuous assistance needed, if internal support is available, the cost of ownership and the complexity. The options offered by these configurable hardware platforms are the design of custom hardware subroutine, in future freeze dates, field upgrades, and the reduction of specific chips from several types of electronic products.

3.3. FPGA method and design tools

Today, FPGAs are more and more present in implementing complex functions. The success or failure of FPGA based system, measured in terms of time-to-market and the final performance reached, depends on the way that the application and its constituent functions are mapped upon platform resources. Low-level languages such as very high-speed integrated circuit hardware description language (VHDL) and Verilog are targeted for conceiving the algorithms carried out in the FPGA chip. Syntax necessitates mapped signals to connect external inputs/outputs to internal signals. These signals are connected to functions which form the algorithms. Once you have created an FPGA design described in hardware description language (HDL), it is substantial to introduce it into a compilation tool that gets the text-based logic to verify it. The traditional design flow is made of such steps from the initial logic synthesis to the final physical design step to achieve FPGA implementation. The objective is to synthesize your HDL to a configuration file that includes informations of the manner to link together the components.

For designs with serious performance goals, designers found that some iteration between synthesis and physical design are crucial to converge to a desired implementation. At consequence, usually, design flow consists of six main steps: hierarchical decomposition, VHDL description, synthesis and optimization, place and route, simulation, programming and configuration. Therefore, potential specifications and these challenges make FPGA technology brightened and used to control system and to handle multi-channel photovoltaic system. In fact, the FPGA device is able to monitor many local control units in a single central unit and prototype the system for practical application.

4. SIMULATION AND EXPERIMENTAL RESULTS

The system is given in section 2 (see in Figure 2) is implemented on FPGA chip. A detailed system operation defined as tracking of maximum power point of multi-channel photovoltaic system is given by Figure 4. The MPPT task on FPGA chip for multiple PV modules is itemized by blocks. The architecture is optimized, aims to develop a single unified MPPT unit of control for all PV modules with reduced time and space.

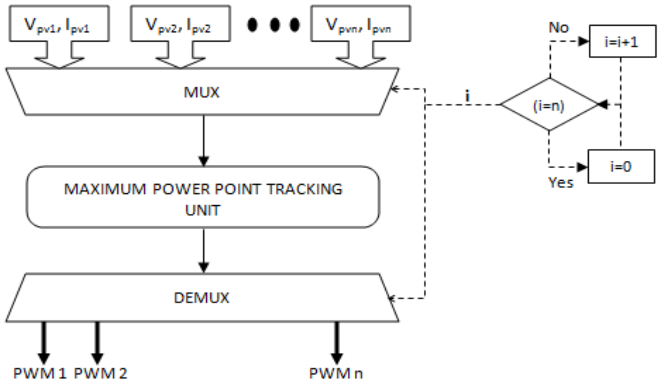

Figure 4. PV system with unified MPPT algorithm for multiple channels

MPPT control unit receives inputs data of voltage and current values. It process on FPGA then it sends the duty ratio to control DC-DC converter switch. The variables V_{pvi} and I_{pvi}, i from 1 to n, are sent alternately in order to compute the duty value for each panel. As an example, the first PV panel obtains the voltage and current updated values $V_{pv1}(k)$ and $I_{pv1}(k)$. Afterwards, MPPT technique uses ancient memorized values of voltage, current and duty, respectively, $V_{pv1}(k-1)$, $I_{pv1}(k-1)$, and $d_{pv1}(k-1)$, to attain a new value of duty ratio, then, it does the same process for the remainder of PV channels until it reaches the optimal value.

This concept ensures that all multi-channel operate synchronously, and each channel operates at its optimal operating point. Using the proposed tracking system reduces the setting of the tracking and facilitates monitoring and controlling multi-channel PV system. In the first step, PV system based on fuzzy MPPT technique is developed using Matlab-Simulink environment. Simulation results of PV system operation are given by Figures 5 and 6.

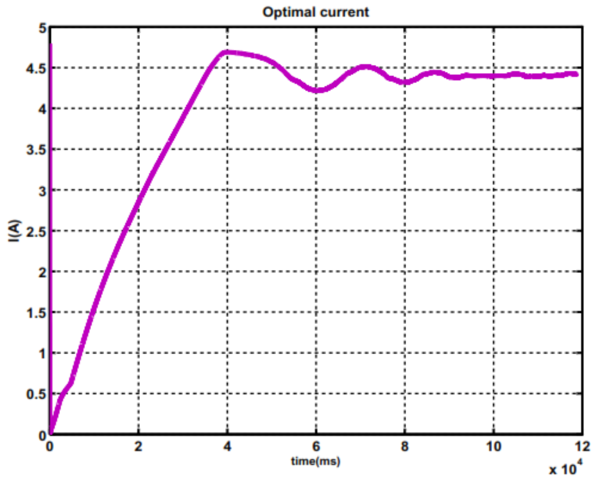

Figure 5. Current curve of PV system

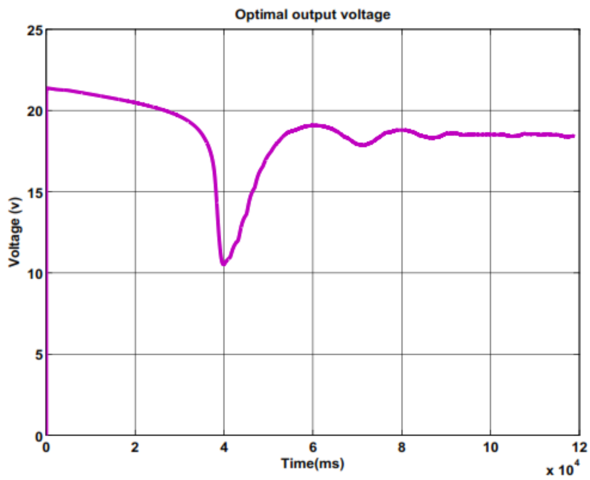

Figure 6. Voltage curve of PV system

Simulation results demonstrate that the PV system operates at optimum values without oscillations at steady state. The photovoltaic system reaches optimal current and voltage as shown by Figures 5 and 6. Then, PV system based on the proposed MPPT approach get better and performing results in term of tracking speed and stability. In a second step, current and voltage data values are retrieved from previous simulations results. These values are provided to design and implement fuzzy logic MPPT controller on FPGA circuit using Quartus platform. Quartus II is defined as a system-on-a-chip development tool. It allows a design of a digital circuit from a traditional schematic form or textual form using a hardware description language: VHDL, Verilog, and A-HDL. Simulation results of MPPT controller on FPGA via Quartus are depicted in Figure 7.

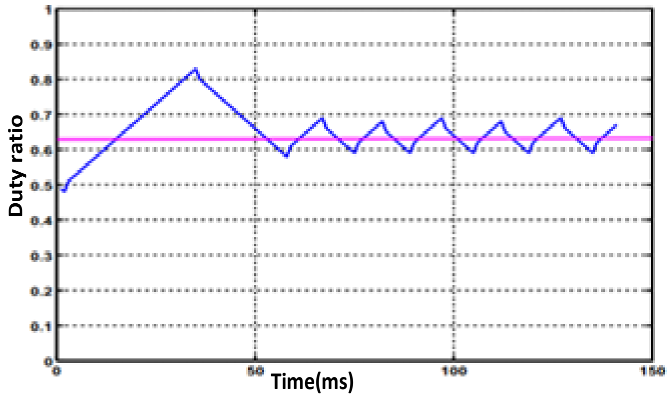

Figure 7. MPP tracking for PV system based on FPGA

The illustration shows that the value of the cyclic ratio demonstrates two phases: a transitional phase and a steady phase. This latest is described by very little oscillations around the optimal value. These oscillations depend on the MPPT algorithm. The theoretical value is equal to 0.64. The resulting optimal value is between 0.6 and 0.68 at the (25 °C, 1000 W/m2). At consequence, we deduce that PV system converges effectively towards its optimal value. Then, we note also that oscillations go to almost disappear, so, the algorithm is accurate and robust.

To prove the efficiency of FPGA based controller for a multi-channel PV system, the MPPT algorithm is implemented on various platforms then execution time is computed. In the first step, fuzzy logic MPPT approach is implemented using software solution. This kind of solution is performed using Arduino devices. Table 1 summarizes the implementation results: execution time and the number of PV channels for each solution.

Table 1. Implementation results

Plateform and device	Arduino-uno	Nios (Stratix III)	Arduino-due (ARM)	FPGA (StratixIII)
Processor frequency (MHz)	16	100	84	-
Execution time (ms)	Limited memory	38.1	18.4	0.1127
PV channels to control	-	13	27	4436

It is clear that FPGA solution is the solution that includes the greatest number of PV channels to control: it is able to control up to 4436 channels. Execution time is in descending order, the minimum rate is achieved by the use of FPGA solution. Therefore, PV system based on FPGA chip allows gathering much power and flexibly control PV channels. For partial shading, as we have mentioned, centralized PV system type is affected. A study case is then given by Table 2.

Table 2. PV panel under irradiation shading

PV panel	Total power (W)	Metrological conditions (°C, W/m2)
1	81.4	25,1000
1	48.6	25,700

The impact on the power and voltage rate is shown in Figure 8. For the first case, PV sytem operates at 25 °C and 1000 W/m2 and at consequence it reaches 81.4 W as total optimal power. For the second case, PV sytem operates at 25 °C and 700 W/m2 and at consequence it reaches 48.6 W as total optimal power. We conclude that the system is changing smoothly from first case to second case. At consequence, the dynamic response of proposed photovoltaic system under metrological changes seems accurate and error-free response. It does not show divergence and does not move away from the new maximum power point.

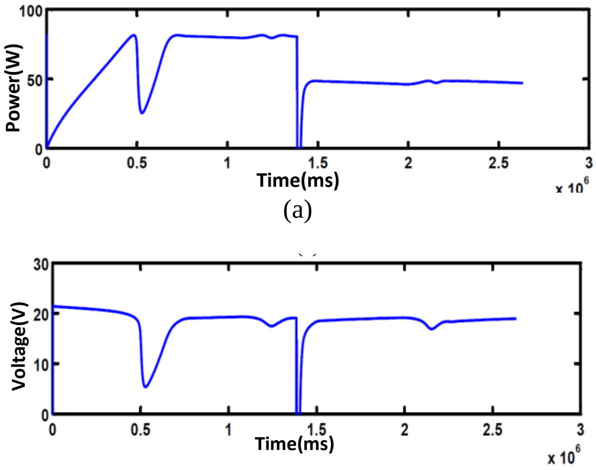

Figure 8. Impact of irradiation shading on PV system for (a) Power and (b) Voltage

5. CONCLUSION

In this study, a fuzzy-based MPPT controller is conceived and carried out on an FPGA chip so as to control multi-channel PV system. Maximum power point tracking is a key technique that ensures photovoltaic panels work at their optimal point. The used approach can deeply improve the tracking speed and reliability. Designing an intelligent MPPT controller for distributed PV system while using FPGA circuit, is arisen to obtain the best speed/cost ratio. Fuzzy MPPT algorithm runs on FPGA to follow the MPP and as the result the PV system performs well at its maximum power. This technique is designed using hardware description language under Quartus tool. Then, it is implemented on FPGA device. A huge number of PV channels are controlled via FPGA. Simulation results reveal major benefits of the proposed-system such as the potential to track the MPP under partial shading, reducing time computation as well as avoid needing multiple MPPT devices. In addition, FPGA device enables advanced shade-tolerant MPPT to sweep for both local and global maxima to maximize I-V curve. The proposed hardware architecture affords high processing with low hardware resource utilization. Consequently, the challenge is raised since FPGA device shows a high ability to integrate a great number of PV channels.

Future work of us will further focus on development our approach and doing other improvements: with the arise of Smart Grid topic, energy sources such as the wind turbine will be included. The contribution of smart technologies allows: a management of the intermittent electricity production (solar and wind), an enhancement in the participation of the consumer and a better energetic efficiency by reducing losses and improving yields. Furthermore, introduce internet of things (IoT) technology in the smart grid is an interesting approach to hasten the cybernation of the electricity grid. Obviously, this technology allows real-time control, precise monitoring and making scientific decision of the system state.

REFERENCES

[1] A. Ramamurthy and S. Bhattacharya, "Optimized digital maximum power point tracker implementation for satellites," in *INTELEC, International Telecommunications Energy Conference (Proceedings)*, Sep. 2008, pp. 1–5, doi: 10.1109/INTLEC.2008.4664126.

[2] G. Liu, W. Wang, P. Wang, S. Jiang, and D. Xu, "Energy conversion and control technology of building integrated photovoltaic," in *Conference Proceedings - 2012 IEEE 7th International Power Electronics and Motion Control Conference - ECCE Asia, IPEMC 2012*, Jun. 2012, vol. 3, pp. 2051–2055, doi: 10.1109/IPEMC.2012.6259158.

[3] A. M. Yasin and M. F. Alsayed, "Fuzzy logic power management for a PV/wind microgrid with backup and storage systems," *International Journal of Electrical and Computer Engineering*, vol. 11, no. 4, pp. 2876–2888, Aug. 2021, doi: 10.11591/ijece.v11i4.pp2876-2888.

[4] Z. Massaq, A. Abounada, and M. Ramzi, "Robust non-linear control of a hybrid water pumping system based on induction motor," *International Journal of Power Electronics and Drive Systems*, vol. 11, no. 4, pp. 1995–2006, Dec. 2020, doi: 10.11591/ijpeds.v11.i4.pp1995-2006.

[5] G. Anil, "Fuzzy logic based maximum power point tracker for a PV System," *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, vol. 5, no. 4, pp. 13–21, 2013.

[6] I. S. B. Hburi, H. Al Khazaali, O. Bayat, and N. H. A. S. Atab, "Maximum power point tracking control for wind turbines with battery storage system," *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 19, no. 2, pp. 564–574, Apr. 2021, doi: 10.12928/TELKOMNIKA.v19i2.16346.

[7] A. Ilyas, M. R. Khan, and M. Ayyub, "FPGA based real-time implementation of fuzzy logic controller for maximum power point

tracking of solar photovoltaic system," *Optik*, vol. 213, p. 164668, Jul. 2020, doi: 10.1016/j.ijleo.2020.164668.
[8] P. D. Kale and D. S. Chaudhari, "A review on maximum power point tracking (MPPT) controlling methods for a photovoltaic system," *International Journal of Emerging Science and Engineering (IJESE)*, vol. 1, no. 5, pp. 15–19, 2013.
[9] S. Venkatesan and M. Saravanan, "Simulation and experimental validation of new MPPT algorithm with direct control method for PV application," *Journal of Renewable and Sustainable Energy*, vol. 8, no. 4, p. 043503, Jul. 2016, doi: 10.1063/1.4959007.
[10] A. Youssef, M. El Telbany, and A. Zekry, "Reconfigurable generic FPGA implementation of fuzzy logic controller for MPPT of PV systems," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 1313–1319, Feb. 2018, doi: 10.1016/j.rser.2017.09.093.
[11] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 439–449, Jun. 2007, doi: 10.1109/TEC.2006.874230.
[12] N. Farah *et al.*, "Fuzzy membership functions tuning for speed controller of induction motor drive: Performance improvement," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 23, no. 3, pp. 1258–1270, Sep. 2021, doi: 10.11591/ijeecs.v23.i3.pp1258-1270.
[13] Z. Massaq, A. Abounada, and M. Ramzi, "Fuzzy and predictive control of a photovoltaic pumping system based on three-level boost converter," *Bulletin of Electrical Engineering and Informatics*, vol. 10, no. 3, pp. 1183–1192, Jun. 2021, doi: 10.11591/eei.v10i3.2605.
[14] A.-A. S. Abdel-Salam and I. N. Jleta, "Fuzzy logic controller design for PUMA 560 robot manipulator," *IAES International Journal of Robotics and Automation (IJRA)*, vol. 9, no. 2, pp. 73–83, Jun. 2020, doi: 10.11591/ijra.v9i2.pp73-83.
[15] C. R. Algarín, J. T. Giraldo, and O. R. Álvarez, "Fuzzy logic based MPPT controller for a PV system," *Energies*, vol. 10, no. 12, p. 2036, Dec. 2017, doi: 10.3390/en10122036.
[16] A. Kumar, P. Chaudhary, and M. Rizwan, "Development of fuzzy logic based MPPT controller for PV system at varying meteorological parameters," in *2015 Annual IEEE India Conference (INDICON)*, Dec. 2015, pp. 1–6, doi: 10.1109/INDICON.2015.7443203.
[17] A. Ahmed, P. Ganeshkumar, J. H. Park, and H. Lee, "FPGA-based centralized controller for multiple PV generators tied to the DC bus," *Journal of Power Electronics*, vol. 14, no. 4, pp. 733–741, Jul. 2014, doi: 10.6113/JPE.2014.14.4.733.
[18] R. Garg, A. Singh, and M. S. Gupta, "Direct current control of grid connected photovoltaic distributed generation system," *American International Journal of Research in Science, Technology, Engineering & Mathematics (AIJRSTEM)*, pp. 123–127, 2013.
[19] N. Femia, G. Lisi, G. Petrone, G. Spagnuolo, and M. Vitelli, "Distributed maximum power point tracking of photovoltaic arrays: novel approach and system analysis," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 7, pp. 2610–2621, Jul. 2008, doi: 10.1109/TIE.2008.924035.
[20] B. Meenakshi Sundaram, B. V. Manikandan, and M. Kaliamoorthy, "Simulation of FPGA controlled single stage boost inverter for the applications of grid connected photovoltaic system," *Simulation*, vol. 93, no. 12, pp. 1087–1097, Dec. 2017, doi: 10.1177/0037549717705466.
[21] I. A. Abed and S. H. Majeed, "Dc/dc converter control using suggested artificial intelligent controllers," *IAES International Journal of Artificial Intelligence*, vol. 10, no. 4, pp. 847–857, Dec. 2021, doi: 10.11591/ijai.v10.i4.pp847-857.
[22] E. Koutroulis, K. Kalaitzakis, and N. C. Voulgaris, "Development of a microcontroller-based, photovoltaic maximum power point tracking control system," *IEEE Transactions on Power Electronics*, vol. 16, no. 1, pp. 46–54, Jan. 2001, doi: 10.1109/63.903988.
[23] R. Akkaya and A. A. Kulaksiz, "A microcontroller-based stand-alone photovoltaic power system for residential appliances," *Applied Energy*, vol. 78, no. 4, pp. 419–431, Aug. 2004, doi: 10.1016/j.apenergy.2003.09.005.
[24] M. A. Fakhfakh, M. Ayadi, and R. Neji, "Implementation of photovoltaic system into microcontroller," in *2012 1st International Conference on Renewable Energies and Vehicular Technology, REVET 2012*, Mar. 2012, pp. 152–155, doi: 10.1109/REVET.2012.6195262.
[25] M. H. Mahmood, I. I. Ali, and O. A. Ahmed, "Design and implementation of intelligent MPPT based on FPGA for PV system," *IOP Conference Series: Materials Science and Engineering*, vol. 881, no. 1, p. 012138, Jul. 2020, doi: 10.1088/1757-899X/881/1/012138.
[26] R. Palanisamy and K. Vijayakumar, "Switching pulse generation for DC-DC boost converter using Xilinx-ISE with FPGA processor," *International Journal of Reconfigurable and Embedded Systems (IJRES)*, vol. 8, no. 2, pp. 81–85, Jul. 2019, doi: 10.11591/ijres.v8.i2.pp81-85.
[27] R. D. and S. R. Rajan, "Simulation and hardware implementation of change in conductance MPPT controller for a solar photovoltaic system using cuk converter," *International Journal of Research in Engineering and Technology*, vol. 02, no. 07, pp. 188–195, Jul. 2013, doi: 10.15623/ijret.2013.0207025.
[28] A. Safari and S. Mekhilef, "Simulation and hardware implementation of incremental conductance MPPT with direct control method using cuk converter," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1154–1161, Apr. 2011, doi: 10.1109/TIE.2010.2048834.
[29] S. Jena, G. Panda, and R. Peesapati, "FPGA-based implementation for improved control scheme of grid-connected PV system with 3-phase 3-level NPC-VSI," *International Journal of Circuit Theory and Applications*, vol. 46, no. 4, pp. 942–964, Apr. 2018, doi: 10.1002/cta.2448.
[30] M. Y. Allani, J. Riahi, S. Vergura, and A. Mami, "FPGA-based controller for a hybrid grid-connected PV/wind/battery power system with AC load," *Energies*, vol. 14, no. 8, p. 2108, Apr. 2021, doi: 10.3390/en14082108.
[31] V. Ramchandani, K. Pamarthi, and S. R. Chowdhury, "Comparative study of maximum power point tracking using linear kalman filter & unscented kalman filter for solar photovoltaic array on field programmable gate array," *International Journal on Smart Sensing and Intelligent Systems*, vol. 5, no. 3, pp. 701–716, Sep. 2012, doi: 10.21307/ijssis-2017-503.
[32] D. Shmilovitz and Y. Levron, "Distributed maximum power point tracking in photovoltaic systems – emerging architectures and control methods," *Automatika*, vol. 53, no. 2, pp. 142–155, Jan. 2012, doi: 10.7305/automatika.53-2.185.
[33] H. Abbes, K. Loukil, H. Abid, M. Abid, and A. Toumi, "Implementation of photovoltaic maximum power point tracking fuzzy logic controller on FPGA," *Journal of Information Assurance and Security*, vol. 11, no. 2, pp. 97–106, 2016.
[34] A. Senthilvel, K. N. Vijeyakumar, and B. Vinothkumar, "FPGA based implementation of MPPT algorithms for photovoltaic system under partial shading conditions," *Microprocessors and Microsystems*, vol. 77, p. 103011, Sep. 2020, doi: 10.1016/j.micpro.2020.103011.
[35] H. Abbes, H. Abid, and K. Loukil, "An improved MPPT incremental conductance algorithm using T-S fuzzy system for photovoltaic panel," *International Journal of Renewable Energy Research*, vol. 5, no. 1, pp. 160–167, 2015, doi: 10.20508/ijrer.76556.
[36] J. Rajewski, "What is an FPGA?," *Alchitry*. https://alchitry.com/what-is-an-fpga (accessed Jan. 17, 2018).
[37] H. Gürsoy and M. Ö. Efe, "Control system implementation on an FPGA platform," *IFAC-PapersOnLine*, vol. 49, no. 25, pp. 425–430, 2016, doi: 10.1016/j.ifacol.2016.12.087.

BIOGRAPHIES OF AUTHORS

Hanen Abbes holder of an electrical engineering diploma from national school of engineering of Sfax, Tunisia in 2012. She gets a Ph.D. thesis degree in computer engineering in December 2017. His current research interests are fuzzy systems, photovoltaic systems and embedded Systems. She has then been investigating the design and implementation issues on FPGA reconfigurable chip. She is the author and co-author of many research and contribution papers published in national and international conferences. She can be contacted at email: hanenabbes2009@yahoo.fr.

Hafedh Abid had an electrical engineering diploma from the National School of Engineering of Sfax, Tunisia in 1989, then a diploma in Electrical and Electronic from the High School of Technical Sciences of Tunis in 1995 and in 1996 the Aggregation in Electric Genius. From 1996 to 2006, he was a 'Technologue' Teacher of the Electric Department in High Institute of Technologies of Sousse. He is working now as a lecturer at National School of Engineering of Sfax, University of Sfax, Tunisia. His current research interests are fuzzy systems and photovoltaic systems. He is the author and co-author of numerous national and international publications. He can be contacted at email: hafedh.abid@enis.tn.

Kais Loukil researcher at "Computer and Embedded System" laboratory, CES-Lab at National School of Engineering, University of Sfax, Tunisia. He is working now as an Assistant Professor at the high school of commerce, Sfax. His current research interests include the design and prototyping of self-adaptive real time multimedia system on chip field. He has then investigating the development of Energy Aware Reconfigurable Node Architecture for Wireless Sensor Network. His current research interests are learning algorithms. He is the author and co-author of several published papers in international conferences. He can be contacted at email: loukil.kais@gmail.com.

Mohamed Abid is the head of "Computer Embedded System" laboratory CES, ENIS, Tunisia (http://www.ceslab.org/eng/perso.php?id=27). Currently, he is working as a Professor at the Engineering National School of Sfax (ENIS), University of Sfax, Tunisia. He get the Ph.D. degree from the National Institute of Applied Sciences, Toulouse, France in 1989. Research interests are: hardware-software co-design, System on Chip, Reconfigurable System, and Embedded System, Wireless Sensor Network etc. He has then been investigating the design and implementation issues on FPGA embedded system. He is the author and co-author of a lot of published papers in national and international books and volumes. He can be contacted at email: mohamed.abid_ces@yahoo.fr.

Ahmed Toumi is an electrical engineer from the Sfax Engineering National School, he has the DEA in instrumentation and Measurement from University of Bordeaux, France in 1981 and the Thesis degree from the University of Tunis in 1985. He joined the National Engineering School as an Associate Professor, since 1981. In 2000, he had the University Habilitation (HDR) from the Engineering School of Safx, Tunisia. He was working as a director of the Electrical Engineering Department in ENIS. Study and research areas touch modelling, stability of electric machines and electrical networks. He can be contacted at email: toumi.a@gmail.com.