RAPORT DE CERCETARE POSTDOCTORALA 2021

CONTRIBUŢII LA OPTIMIZAREA PRODUCTIEI DE ENERGIE ELECTRICA UTILIZAND CONVERSIA FOTOVOLTAICA IN SISTEME COMPLEXE AVANSATE

Postdoc: **Dr. Ing. Dan CRĂCIUNESCU**
Mentor: **Prof. Dr. Ing. Laurentiu FARA***

BUCUREŞTI 2021

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Journal: Energies
Manuscript ID: energies-1523808
Title: Intelligent Approach of Fuzzy Logic Controller for High Efficiency and Optimization of the Photovoltaic System Performances
Authors: Dan Craciunescu, Laurentiu Fara *

Received: 08 December 2021
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Authors: Dan Craciunescu, Laurentiu Fara *
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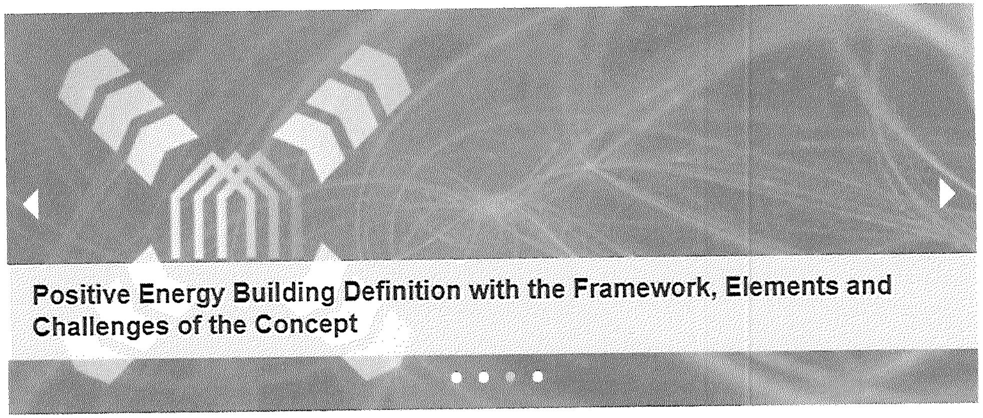

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Acest program postdoctoral nu ar fi fost complet fără implicarea deosebita a Domnului **Prof. univ. dr. ing. Laurențiu FARA** căruia țin să îi mulțumesc in mod deosebit pentru timpul și consultanța științifică prețioasă acordata pe perioada acestuia cat si pentru îndrumarea si încurajarea acordata pe parcursul stagiului de cercetare, asigurându-l pe aceasta cale de întreaga mea considerație.

Doresc să mulțumesc, în mod deosebit, **ACADEMIEI OAMENILOR DE STIINTA DIN ROMANIA (AOSR),** pentru susținerea tinerilor cercetători si aportul adus la formarea calităților de cercetător, sincere mulțumiri si sentimente de recunoștința pentru sprijinul acordat precum si pentru oportunitățile si perspectivele de dezvoltare profesionala de care am beneficiat prin intermediul programului de cercetare Postdoctorala.

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BUCURESTI

Optimization of Performances and Reliability for Building Integrated Photovoltaic Systems (BIPV)

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Bucharest 2021

HIGHLIGHTS

(1) Innovative contribution based on Fuzzy Logic Controller (FLC) to detect sudden weather conditions and rapidly changing uncertainties in specific applications of PV systems.

(2) Analyses of the influence of the temperatures and solar irradiance on the characteristics and main parameters of the PV generator.

(3) Operational optimisation of the PV system based on FLC managed to stabilise and improve its output performances from the point of view of safety in power supply of the load.

(4) Unifying approach of PV systems to increase their efficiency integration for specific application.

COVER LETTER

To: *the Editor of ENERGIES, Special Issue on "Analysis and Numerical Modeling in Solar Photovoltaic Systems".*

Dear Editor,

I submit now the manuscript entitled: **Intelligent Approach of Fuzzy Logic Controller for High Efficiency and Optimization of the Photovoltaic System Performances,** authors: ***Dan CRACIUNESCU, Laurentiu FARA.***

The author studied one of the main intelligent methods for the Maximum Power Point Tracking (MPPT) providing an innovative approach based on Fuzzy Algorithm in varying weather conditions and rapidly changing uncertainties. Fuzzy Logic Controller (FLC) is obtained by implementing a Fuzzy Algorithm in a specialized software (MATLAB / Simulink) and could detect the sudden changes and heuristic variables for a power control system used in specific applications.

The article highlights the development and implementation of a numerical simulation model for determining the MPPT that used FLC for a photovoltaic system considered for analysis. It is described the foundation of the research and the motivation that led to this work. The study analyzed and discussed the influence of the temperature and solar irradiance on the characteristics and main parameters of the PV generator, as well as the operational optimization of the PV system based on FLC benefit. The authors managed to stabilize and improve the output performances of the PV system from the point of view of safety in power supply of the load. The results could be developed and applied for stand-alone and on-grid complex PV systems.

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I am looking for that the present manuscript will be published after its Review in the Special Issue of Energies on "Analysis and Numerical Modeling in Solar Photovoltaic Systems".

Sincerely yours,

Laurentiu FARA
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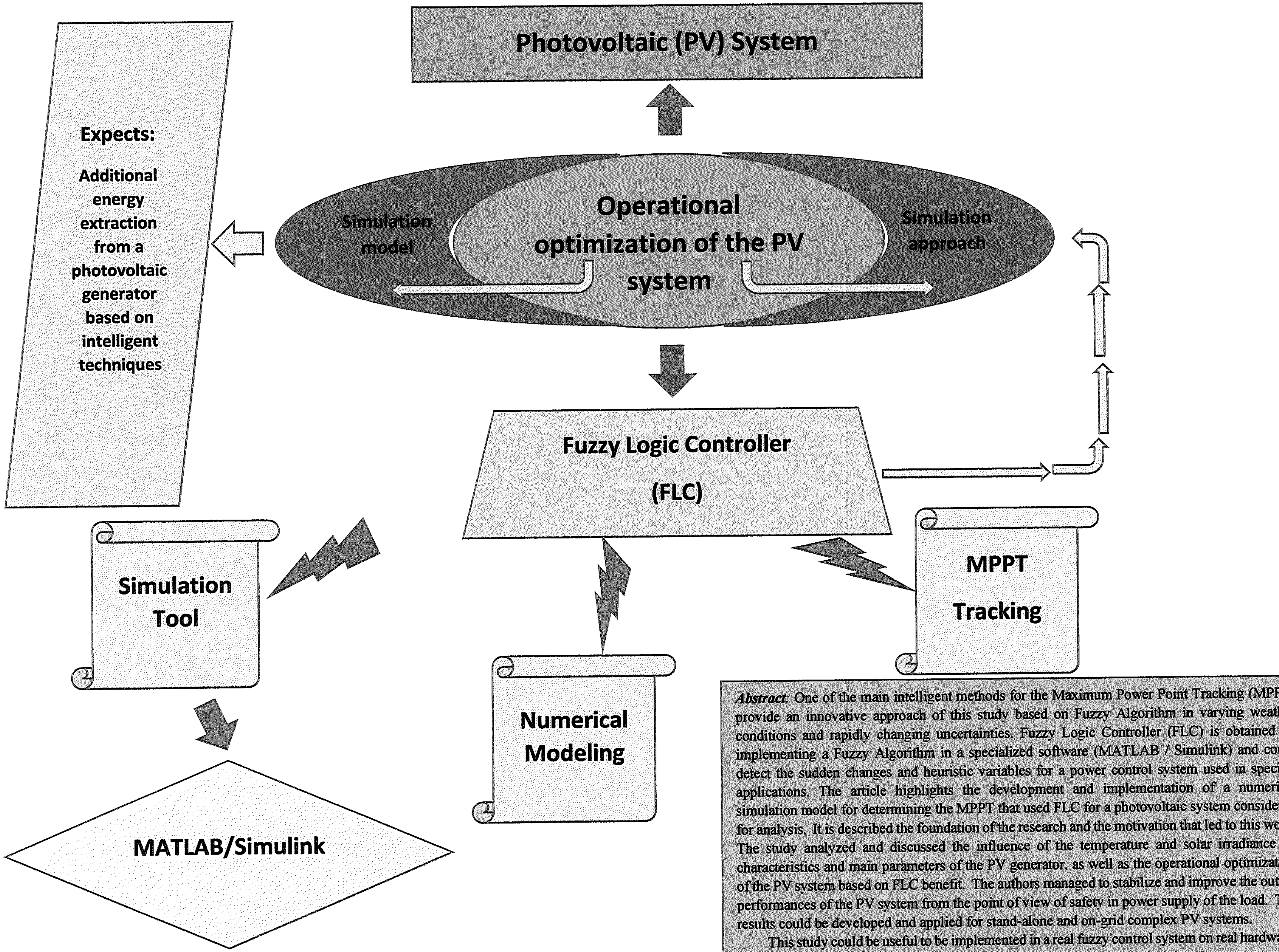

Abstract: One of the main intelligent methods for the Maximum Power Point Tracking (MPPT) provide an innovative approach of this study based on Fuzzy Algorithm in varying weather conditions and rapidly changing uncertainties. Fuzzy Logic Controller (FLC) is obtained by implementing a Fuzzy Algorithm in a specialized software (MATLAB / Simulink) and could detect the sudden changes and heuristic variables for a power control system used in specific applications. The article highlights the development and implementation of a numerical simulation model for determining the MPPT that used FLC for a photovoltaic system considered for analysis. It is described the foundation of the research and the motivation that led to this work. The study analyzed and discussed the influence of the temperature and solar irradiance on characteristics and main parameters of the PV generator, as well as the operational optimization of the PV system based on FLC benefit. The authors managed to stabilize and improve the output performances of the PV system from the point of view of safety in power supply of the load. The results could be developed and applied for stand-alone and on-grid complex PV systems.

This study could be useful to be implemented in a real fuzzy control system on real hardware. It will be the subject of future research to be developed by the authors.

Intelligent Approach of Fuzzy Logic Controller for High Efficiency and Optimization of the Photovoltaic System Performances

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Abstract:

One of the main intelligent methods for the Maximum Power Point Tracking (MPPT) provide an innovative approach of this study based on Fuzzy Algorithm in varying weather conditions and rapidly changing uncertainties. Fuzzy Logic Controller (FLC) is obtained by implementing a Fuzzy Algorithm in a specialized software (MATLAB / Simulink) and could detect the sudden changes and heuristic variables for a power control system used in specific applications.

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Keywords: Photovoltaic System, Efficiency, MPPT, FLC, Performance, MATLAB/Simulink, Artificial Intelligence, MATLAB/Simulink

1. Introduction

The increase in electricity dependence of the current population has led to an increase in the electricity produced. High demand for electricity supply has also forced concerns about the quality aspects of electricity, namely energy production to be reliable and stable, thus increasing consumer safety in terms of electricity supply. Unfortunately, the qualitative aspects of electricity produced from renewable sources are not yet favorable to the energy system, raising problems of compatibility with the electricity grid [1-3]. There are a number of concerns about increasing the conversion efficiency of photovoltaic (PV) solar cells. In present the maximum conversion efficiency of solar cells is about 47% under laboratory conditions [3, 4]. Due to the fact that the conversion rate is still low, various methods of improving electrical efficiency for building integrated photovoltaic systems (BIPV) are being considered, such as the use of Maximum Power Point Tracking (MPPT), the implementation of various Fuzzy Logic-based techniques, as well as the development of artificial intelligence technologies [4, 5]. In literature, the artificial intelligence (AI) technologies considered for photovoltaic systems are represented by the following algorithms, [6, 7]: **(1)** neural network (NN); **(2)** fuzzy logic (FL); **(3)** simulated annealing (SA); **(4)** genetic algorithm (GA); **(5)** ant colony (ACO); **(6)** particle swarm (PSO) and **(7)** hybrid techniques, such as adaptive neuron fuzzy inference systems (ANFIS), GA-fuzzy, and NN-fuzzy [8-14].

Various applications of artificial intelligence (AI) for PV systems can be studied: **(1)** Detection of incidents, either using unsupervised learning or by comparing measured data with simulated electrical measurements; **(2)** Detection of short-circuit failures of photovoltaic networks using artificial neural networks (ANN) [15, 16]; **(3)** Hierarchical methods for diagnosing anomalies depending on the context, to identify the automatic operating conditions of individual strings; **(4)** Prediction of pollution effects using a Bayesian neural network and polynomial regressions [12]. Based on these applications, the following qualities of AI algorithms have been established, [17, 18]: **(a)** ANFIS with more precision in the applications of parameter identification compared to GA and SA. **(b)** NN with the highest accuracy obtained in the sizing of photovoltaic systems and the maximum power tracking point (MPPT); **(c)** fuzzy controllers and fuzzy hybrid controllers are the most commonly used MPPT control devices. **(d)** GA achieves the highest accuracy in solar tracking applications. **(e)** NN is the most widely used algorithm for fault diagnosis. AI

† **Corresponding Author**

algorithms could provide an alternative method of sizing PV pumping systems in many regions that do not have complete data [19, 20].

In order to achieve a high level of performance and implicitly of competitiveness of photovoltaic systems, it is necessary to perform individual analyzes on each type of PV system, respectively on each type of application in which they can be integrated and correlated with the energy performances of the studied PV systems to elaborate an efficient strategy. The operational optimization of photovoltaic systems is possible through the use and optimization of MPPT and FLC algorithms that lead to the improvement of the electrical performance of PV systems in fluctuating operating conditions (random meteorological parameters).

In the present article, we aimed to increase the performance of PV systems by adopting a modified FLC algorithm and implemented it in the MATLAB / Simulink environment. On this basis it is possible to increase the output power of photovoltaic systems, as well as optimization from the point of view of the electricity consumer. The implementation of the optimization of photovoltaic systems was done by:

(1) optimizing the operation of photovoltaic systems from the point of view of the temperature and solar irradiance influence on the PV generator performances;

(2) increasing the electricity production of PV systems, with the ultimate goal of integrating them in specific applications with different degree of difficulty and use.

The main objective of this article is to develop a unifying approach of photovoltaic systems in order to increase their efficient integration for specific applications, as well as the analysis and implementation of numerical models, resulting in increasing and user confidence.

The innovative contribution of this study was to adapt and develop an improved numerical simulation model, based on artificial intelligence technique available in the MATLAB Simulink work environment , with direct implication for increasing the performance of photovoltaic systems, in order to respond efficiently to the fluctuating character of the output parameters of the PV generator, respectively in obtaining notable results regarding the behavior and evolution of the electrical parameters of the PV systems in different conditions.

The potential of digitalization approach based on Machine Learning(ML), Digital Twin(DT) and Internet of Things(IoT) techniques could be followed up in future studies in the context of sustainable development, characterization, and operational optimization of photovoltaic systems.

2. Knowledge and state of the art for a specific application of nZEB PV systems

The photovoltaic technology developed by one of the important companies in the field, namely SunPower, has a major impact, contributing to the development of some of the most ambitious and futuristic projects in the world. Thus, the city of Masdar from Abu Dhabi Emirate, represents a developing global technology cluster, with the aim of being one of the most sustainable urban areas in the world, powered by renewable energy. By 2017, over 6,000 SunPower E19 / 315 W panels were installed in Masdar, both on the facades of the buildings, where shading and production of "green" energy is ensured, as well as on their roofs.

The sophisticated campus in this city offers an ideal framework for innovation and real development of new PV technologies. At the same time, the Masdar Institute, in collaboration with IRENA (International Renewable Energy Agency) aims to certify the ESTIDAMA Pearl Building Rating System, one of the strictest standards of energy efficiency and sustainability in the world [21]. The main objective of the PV program for the city of Masdar is to produce 7% renewable energy from the country's energy potential by 2020 [21].

The Masdar Institute hosts both educational institutions, and important actors in the energy field, such as Siemens Electric Company and the International Renewable Energy Agency (located in an nZEB - Nearly Zero Energy Building), which contributed to the development and implementation of pilot projects based on PV systems [22].

Residential buildings in Masdar city are governed by well-defined standards, which provide heights up to five floors for buildings built on narrow streets and which must be equipped with roofs covered with PV modules and solar tarpaulins at street level, which ensures both the shading of the sidewalk, and the production of electricity (see **Figure 1**).

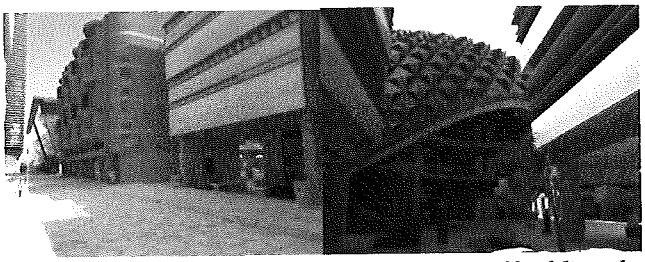


Fig. 1: *Architecture of integrated photovoltaic systems in the structure of buildings located on the campus of the Masdar Institute, Abu Dhabi* ‡

‡ Photo taken by Dan CRACIUNESCU, one of the authors of this work during his visit to the Masdar Institute, Abu Dhabi, on the occasion of the SWC2017 Congress

There are also other challenges to the pilot project developed by the Masdar Institute, such as the sustainable development of photovoltaic technology (PV modules) for both land and air transport (see **Figure 2**). In this respect, alternative smart buses (up to 4 people) that do not have manual operation (they are fully automated) have been developed and tested. The Masdar Institute also presents a daring project in relation to alternative airplanes using solar energy [23].

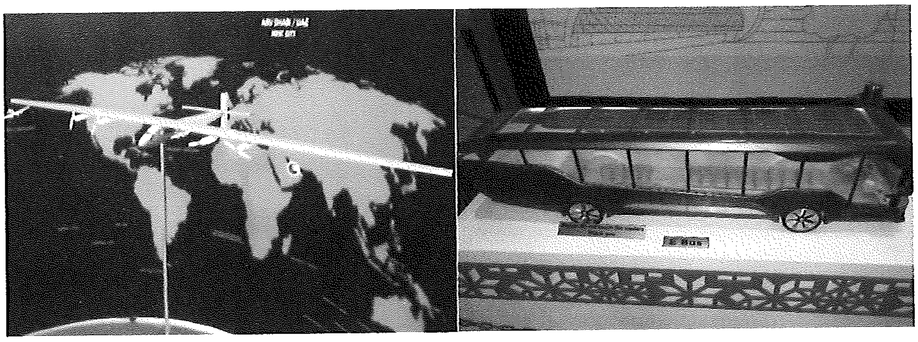


Fig. 2: *Pilot project based on the sustainable development of transport means based on the use of photovoltaic technology developed by the Masdar Institute, Abu Dhabi* §

The energy strategy of Masdar City presented in **Figure 3** consists in the exclusive use of renewable energy and in particular the production of the city's electricity demand using photovoltaic systems. The Abu Dhabi region, which also includes Masdar, uses 62% of the emirate's electricity [24]. At the same time, a considerable amount of electricity produced in the town of Masdar will be directed and used in the desalination of water and will be produced using central power solar systems with concentrators (based on tower and heliostats field).

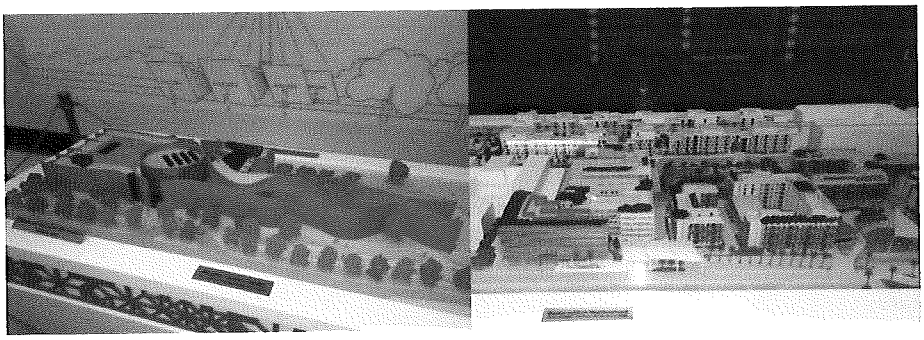


Fig. 3: *Pilot project for Masdar town based on the use of photovoltaic technology developed by the Masdar Institute, Abu Dhabi* [3]

3. Numerical modelling and simulation tool

3.1 Modeling and simulation techniques applied for PV systems

The design of the stand-alone photovoltaic system was fully developed in MATLAB/Simulink to characterize the components of the PV system.

This section describes the procedure used to simulate the electrical characteristics of the PV generator, namely the I-V and P-V characteristics, respectively the output power of the photovoltaic system. An important aspect is how the structure of the PV matrix is defined and implemented in MATLAB, as the performance of the system depends mainly on it. PV system modeling is based on modular blocks. A modular structure facilitates efficient modeling of other system structures and the replacement of their components, such as a DC load instead of an AC load. The MATLAB / Simulink tool has features that can be used to improve the understanding and simulation of I-V and P-V characteristics for stand-alone photovoltaic systems, as it has a user-friendly interface. It can also be used to study the effect of temperature and solar irradiance, the variation of shading patterns characterized by multiple peaks in characteristic curves, and which disrupt the efficiency of the system by default affecting the load. A notable advantage of this approach in the MATLAB work environment is the fact that once created the photovoltaic generator model it

§,3 Photo taken by Dan CRACIUNESCU, one of the authors of this work during his visit to the Masdar Institute, Abu Dhabi, on the SWC2017 Congress can be later interfaced with current system models that make it possible to simulate complex photovoltaic systems and their interaction with other systems. A major advantage of using MATLAB software is due to its availability in most academic research and industrial organizations, being useful for a wide range of engineering disciplines. It also offers some features that can be used to simulate very complex systems, circuits, electronic and power systems. **Figure 4** shows the conceptual electrical configuration of a PV stand-alone(autonomous) system.

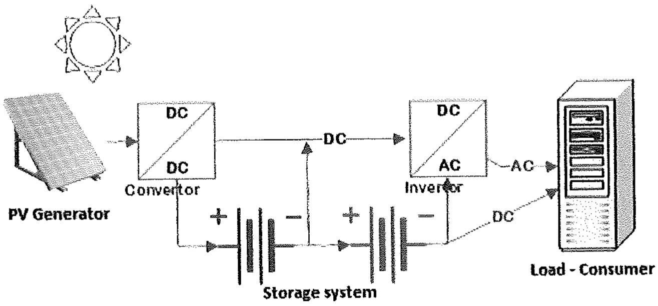


Fig. 4: *Conceptual configuration of an autonomous photovoltaic system*

3.2 The theoretical aspects of Fuzzy Logic Controller (FLC).

The mathematical model underlying fuzzy logic is presented below, taking into account the most accurate definition of the terminology that characterizes this method, namely: variables, values, and rules in fuzzy language [25 - 30]. After choosing the FLC inputs and outputs, there must be a language description for each of the respective input and output sizes. For a fuzzy system, we will describe the fuzzy input as u_i and its variable as $\hat{u}_i$ and for the output we will have y_i ; the output size variable will also be described as in the case of the input variable, $\hat{y}_i$. After establishing the input or output of the FLC, a description of each variable must be made, namely $\hat{u}_i$ and $\hat{y}_i$. **Figure 5** shows the fuzzy block diagram that converts the actual number of input values to fuzzy sets, and then through the inference mechanism (that uses specific fuzzy or basic rules to produce the default fuzzy sets or fuzzy conclusions that ultimately serve to setting the output values) the FLC outputs are obtained. To perform the FLC we will repeat the following steps, namely we will fuse the two input variables using standardized fuzzy sets for each of the three triangular member functions (MFs): Small, Medium, and High, as it is shown in **Figure 6**.

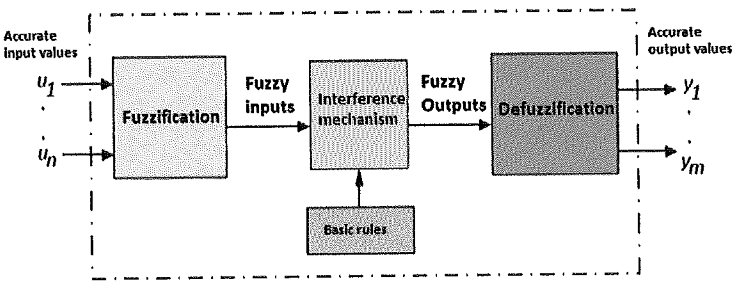
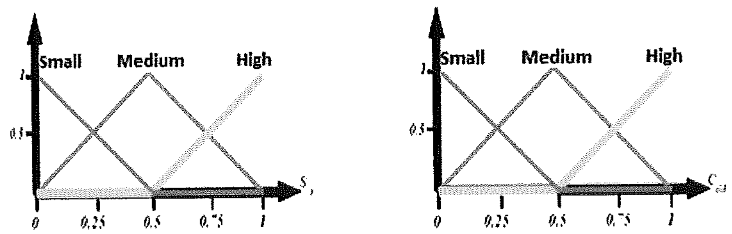


Fig. 5: *Fuzzy Block diagram*



a) b)

Fig.6: *a) Membership of the first entry (absolute value S_a), b) the function of member of the second entry (C_{old})*

The mathematical characterization of the triangular member entry function is shown below:

$$\mu^{small}(u) = \begin{cases} 1 & if\ u \leq 0 \\ \max\left\{0,1 - \frac{u}{0.5}\right\} & otherwise \end{cases} \quad (1)$$

$$\mu^{medium}(u) = \begin{cases} \max\left\{0,1 + \frac{u-0.5}{0,5}\right\} & if\ u \le 0.5 \\ \max\left\{0,1 + \frac{0.5-u}{0.5}\right\} & otherwise \end{cases} \quad (2)$$

$$\mu^{high}(u) = \begin{cases} max\left\{0,1 + \frac{u-0.5}{0.5}\right\} & if\ u \le 1 \\ 1 & otherwise \end{cases} \quad (3)$$

The output variable consists of a normalized fuzzy set of five triangular MFs: Large Negative (NB), Low Negative (NS), Zero (ZO), Small Positive (PS), and Large Positive (PB), as it is shown in **Figure 7**. The mathematical characterization of the membership for the triangular function is presented below in the relations (4)-(8).

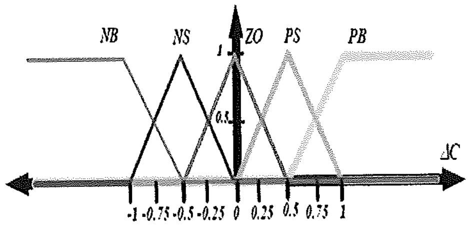


Fig. 7: *Exit membership ΔC*

$$\mu^{NB}(\Delta C) = \begin{cases} 1 & if\ \Delta C \le -1 \\ max\left\{0,1 + \frac{-1-\Delta C}{0.5}\right\} & otherwise \end{cases} \quad (4)$$

$$\mu^{NS}(\Delta C) = \begin{cases} max\left\{0,1 + \frac{\Delta C+0.5}{0,5}\right\} & if\ \Delta C \le -0.5 \\ max\left\{0,1 + \frac{-0.5+\Delta C}{0.5}\right\} & otherwise \end{cases} \quad (5)$$

$$\mu^{ZO}(\Delta C) = \begin{cases} max\left\{0,1 + \frac{\Delta C}{0,5}\right\} & if\ \Delta C \le 0 \\ max\left\{0,1 + \frac{-\Delta C}{0.5}\right\} & otherwise \end{cases} \quad (6)$$

$$\mu^{PS}(\Delta C) = \begin{cases} max\left\{0,1 + \frac{\Delta C-0.5}{0,5}\right\} & if\ \Delta C \le 0.5 \\ max\left\{0,1 + \frac{0.5-\Delta C}{0.5}\right\} & otherwise \end{cases} \quad (7)$$

$$\mu^{PB}(\Delta C) = \begin{cases} max\left\{0,1 + \frac{\Delta C-1}{0.5}\right\} & if\ \Delta C \le 1 \\ 1 & otherwise \end{cases} \quad (8)$$

Depending on the value of the absolute power slope, the Power-Voltage characteristics of the PV panel is divided into three regions, as it is shown in **Figure 8**. Given the old C_{old} disturbance stage, the FLC controller will cause the change to the new step to reach the MPP.

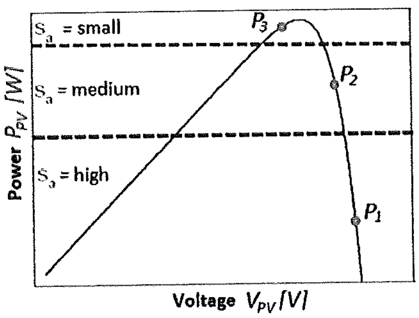


Fig. 8: *Power-Voltage characteristics of the PV panel with FLC based on P&O*

a) Fuzzification:

Assuming that the operating point is at **P1**, where the absolute value of the slope S_a is high, then it means that the operating point is far from MPP. The old step can have three different values in this case. If C_{old} is small then the change in the step size ΔC must be large positive (PB) to reach MPP quickly. If C_{old} is medium, the change in the step size ΔC must be small positive (PS) to reach the MPP without oscillating around it. Finally, if C_{old} is large, the change in step size ΔC must be Zero (ZO) to avoid overtaking the MPP in the opposite direction leading to oscillations. As a result, S_a determines three rules, each with its premise and conclusion, as follows:

- **For the operating point P1**

- If S_a is high and C_{old} is small then ΔC is positively high

$$\mu_{premise\,(1)} = min\left(\mu_{high}(S_a), \mu_{small}\,(C_{old})\right) \tag{9}$$

$$\mu_{(1)}(\Delta C) = min\,\{\mu_{PB}(\Delta C), \mu_{premisa\,(1)}\} \tag{10}$$

- If S_a is high and C_{old} is medium, then ΔC is positive small

$$\mu_{premise\,(2)} = min(\mu_{high}(S_a), \mu_{medium}\,(C_{old})) \tag{11}$$

$$\mu_{(1)}(\Delta C) = min\,\{\mu_{PS}(\Delta C), \mu_{premise\,(2)}\} \tag{12}$$

- If S_a is high and C_{old} is high, then ΔC is zero

$$\mu_{premise\,(3)} = min(\mu_{high}(S_a), \mu_{high}\,(C_{old})) \tag{13}$$

$$\mu_{(3)}(\Delta C) = min\,\{\mu_{ZO}(\Delta C), \mu_{premise\,(3)}\} \tag{14}$$

Assuming that the operating point is at **P2**, where the absolute value of the slope S_a is average, then it means that the operating point is closer to the MPP than in the previous case, but still does not give it up. The old step can also have three different values in this case. If C_{old} is small, then the change in step size ΔC must be small positive (PB) to reach the MPP without oscillating around it. If C_{old} is medium, the change in step size ΔC must be zero (ZO) to avoid overtaking the MPP in the opposite direction leading to oscillations. Finally, if C_{old} is large, the change in step size ΔC must be negatively small (NS) so as not to exceed MPP. As a result, Sa determines three rules, each with its premise and conclusion, as follows:

- **For the operating point P2**

- If S_a is medium and C_{old} is small, then ΔC is positive small

$$\mu_{premise\,(4)} = min(\mu_{medium}(S_a), \mu_{small}\,(C_{old})) \tag{15}$$

$$\mu_{(4)}(\Delta C) = min\,\{\mu_{PS}(\Delta C), \mu_{premise\,(4)}\} \tag{16}$$

- If S_a is medium and C_{old} is medium, then ΔC is zero

$$\mu_{premise\,(5)} = min(\mu_{medium}(S_a), \mu_{medium}\,(C_{old})) \tag{17}$$

$$\mu_{(5)}(\Delta C) = min\,\{\mu_{ZO}(\Delta C), \mu_{premise\,(5)}\} \tag{18}$$

- If S_a is medium and C_{old} is high, then ΔC is negative small

$$\mu_{premise\,(6)} = min(\mu_{medium}(S_a), \mu_{high}\,(C_{old})) \tag{19}$$

$$\mu_{(6)}(\Delta C) = min\,\{\mu_{NS}(\Delta C), \mu_{premise\,(6)}\} \tag{20}$$

Assuming that the operating point is at **P3**, where the absolute value of the slope S_a is small, then it means that the operating point is close to the MPP. The old step can have three different values in this case. If C_{old} is small, then the change in step size ΔC must be zero (ZO) to avoid overtaking the MPP in the opposite direction leading to oscillations. If C_{old} is medium, the change in step size ΔC must be negative small (NS), so as not to exceed MPP. Finally, if C_{old} is large, the change in step size ΔC must be large negative (NB) so as not to exceed MPP.

As a result, S_a determines three rules, each with its premise and conclusion, as follows:

- **For the operating point P3**

- If S_a is small and C_{old} is small, then ΔC is zero

$$\mu_{premise\ (7)} = min(\mu_{small}(S_a), \mu_{small}\ (C_{old})) \tag{21}$$

$$\mu_{(7)}(\Delta C) = min\ \{\mu_{ZO}(\Delta C), \mu_{premise\ (7)}\} \tag{22}$$

- If S_a is small and C_{old} is medium, then ΔC is negative small

$$\mu_{premise\ (8)} = min(\mu_{smallc}(S_a), \mu_{medium}\ (C_{old})) \tag{23}$$

$$\mu_{(8)}(\Delta C) = min\ \{\mu_{NS}(\Delta C), \mu_{premise\ (8)}\} \tag{24}$$

- If Sa is small and Cold is high, then ΔC is negative high

$$\mu_{premise\ (9)} = min(\mu_{mic}(S_a), \mu_{high}\ (C_{old})) \tag{25}$$

$$\mu_{(9)}(\Delta C) = min\ \{\mu_{NB}(\Delta C), \mu_{premise\ (9)}\} \tag{26}$$

The FLC rules are presented in **Table 1**. The premise, which is the first part of the rule, is calculated using the minimum inference operator. The inference operator compares the rules for each of the MF inputs and chooses the minimum rule.

Table 1: *FLC rules*

C_{old} / $S_a = dP/dV$	Small	Medium	High
Small	ZO	NS	NB
Medium	PS	ZO	NS
High	PB	PS	ZO

The last step in the FLC process is defusing, which takes the default fuzzy set and turns it back into a real number or an exact output.

b) Defuzzification:

$$\Delta C^{real} = \frac{(-1)\int u_{(9)}\,(\Delta C)+(-0.5)\int u_{(8)}\,(\Delta C)+(0)\int u_{(7)}\,(\Delta C)}{\sum_{i=1}^{9}\int u_i\,(\Delta C)} + \frac{(-0.5)\int u_{(6)}\,(\Delta C)+(0)\int u_{(5)}\,(\Delta C)+(0.5)\int u_{(4)}\,(\Delta C)}{\sum_{i=1}^{9}\int u_i\,(\Delta C)} + \frac{(0)\int u_{(3)}\,(\Delta C)+(0.5)\int u_{(2)}\,(\Delta C)+(1)\int u_{(1)}\,(\Delta C)}{\sum_{i=1}^{9}\int u_i\,(\Delta C)} \tag{27}$$

Substituting with the values in the above equation with the premises we obtain:

$$\Delta C^{real} = \frac{(-1)\left(\mu_{premise\,(9)} - \frac{(\mu_{premise\,(9)})^2}{2}\right)+(-0.5)\left(\mu_{premisa\,(8)} - \frac{(\mu_{premise\,(8)})^2}{2}\right)}{\sum_{i=1}^{9}\int u_i\,(\Delta C)} + \frac{(-0.5)\left(\mu_{premise\,(6)} - \frac{(\mu_{premise\,(6)})^2}{2}\right)+(0.5)\left(\mu_{premisa\,(4)} - \frac{(\mu_{premise\,(4)})^2}{2}\right)}{\sum_{i=1}^{9}\int u_i\,(\Delta C)} + \frac{(-1)\left(\mu_{premise\,(2)} - \frac{(\mu_{premise\,(9)})^2}{2}\right)+(-0.5)\left(\mu_{premisa\,(9)} - \frac{(\mu_{premise\,(2)})^2}{2}\right)}{\sum_{i=1}^{9}\int u_i\,(\Delta C)} \tag{28}$$

where:

$$\sum_{i=1}^{9}\int u_i\ (\Delta C) = \left(\mu_{premise\ (9)} - \frac{(\mu_{premise\,(9)})^2}{2}\right) + \left(\mu_{premise\ (8)} - \frac{(\mu_{premise\,(8)})^2}{2}\right) + \left(\mu_{premisa\ (7)} - \frac{(\mu_{premise\,(7)})^2}{2}\right) + \left(\mu_{premise\ (6)} - \frac{(\mu_{premise\,(6)})^2}{2}\right) + \left(\mu_{premise\ (5)} - \frac{(\mu_{premise\,(5)})^2}{2}\right) + \left(\mu_{premise\ (4)} - \frac{(\mu_{premise\,(4)})^2}{2}\right) + \left(\mu_{premise\ (3)} - \frac{(\mu_{premise\,(3)})^2}{2}\right) + \left(\mu_{premise\ (2)} - \frac{(\mu_{premise\,(2)})^2}{2}\right) + \left(\mu_{premise\ (1)} - \frac{(\mu_{premise\,(1)})^2}{2}\right)$$

To obtain the final equations in the relations (27) and (28) two functions are introduced, respectively f_1 and f_2:

$$\Delta C^{real} = -0.5\, f_1\ (S_a, C_{old}) + 0.5\, f_2\ (S_a, C_{old}) \tag{29}$$

where:

$$f_1\left(S_a, C_{old}\right) = \frac{2\left(\mu_{premise\,(9)} - \frac{\left(\mu_{premise\,(9)}\right)^2}{2}\right) + \left(\mu_{premise\,(8)} - \frac{\left(\mu_{premise\,(8)}\right)^2}{2}\right)}{\sum_{i=1}^{9} \int u_i\,(\Delta C)} + \frac{\left(\mu_{premise\,(6)} - \frac{\left(\mu_{premise\,(6)}\right)^2}{2}\right)}{\sum_{i=1}^{9} \int u_i\,(\Delta C)}$$

$$f_2\left(S_a, C_{old}\right) = \frac{2\left(\mu_{premise\,(4)} - \frac{\left(\mu_{premise\,(4)}\right)^2}{2}\right) + \left(\mu_{premise\,(2)} - \frac{\left(\mu_{premise\,(2)}\right)^2}{2}\right)}{\sum_{i=1}^{9} \int u_i\,(\Delta C)} + \frac{\left(\mu_{premise\,(1)} - \frac{\left(\mu_{premise\,(1)}\right)^2}{2}\right)}{\sum_{i=1}^{9} \int u_i\,(\Delta C)}$$

3.3 Implementation of the simulation tool for the adapted FLC algorithm to a PV system

A) MPPT-based FLC controller for the PV generator

Maximum Power Point Tracking is implemented using an incremental algorithm and a logic fuzzy controller. The incremental algorithm compares the actual power of the PV system (P_{PV}) with the estimated value for the maximum power (reference power) (P_r), via the FLC controller, at equal time intervals. The output of the FLC controller is used to direct the reference power to a new level, which is added to the previous value of each interval. The highest value of power can be considered as the maximum power. The output signal from the FLC controller is routed to a PWM (Pulse Width Modulation) to control the operating cycle of the DC-DC voltage converter. The DC-DC converter raises the voltage to the value at which the PV system can operate at full power. To implement the FLC-based MPPT technique we used the Fuzzy tool from MATLAB Fuzzy to design the FLC controller. The first step in implementing the controller is to define the FLC design parameters (inputs, outputs, defuzzification method) in the FIS (Fuzzy Inference System) editor, as it is shown in **Figure 9**, then each member function is defined and named as it is shown in **Figure 10 a, b,** and **c.**

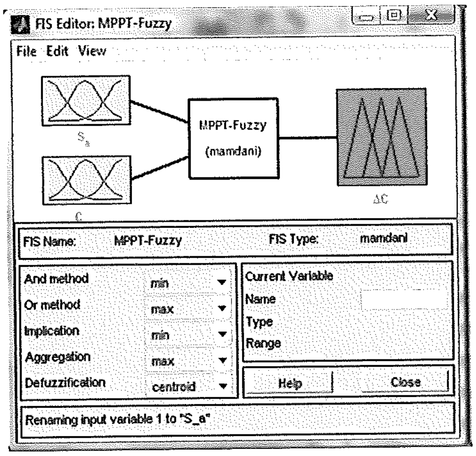
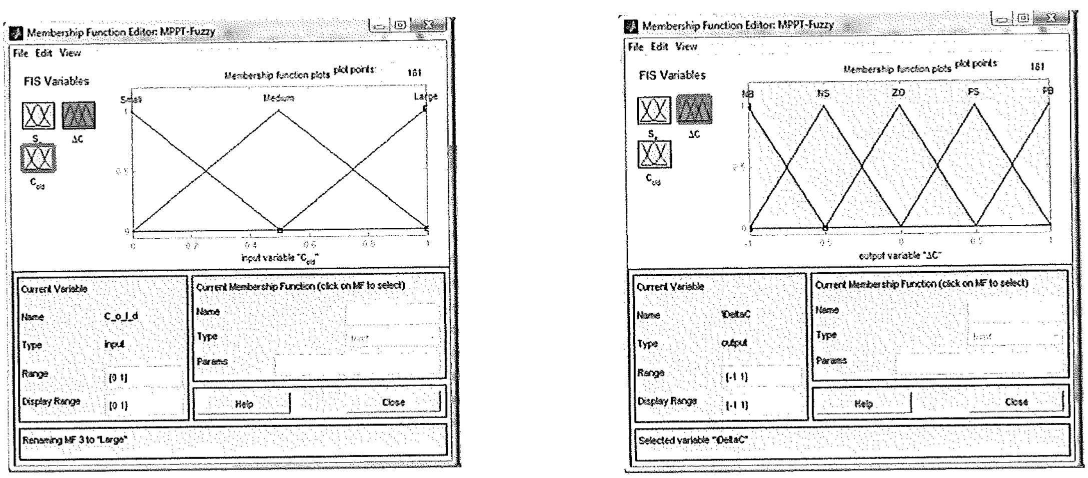
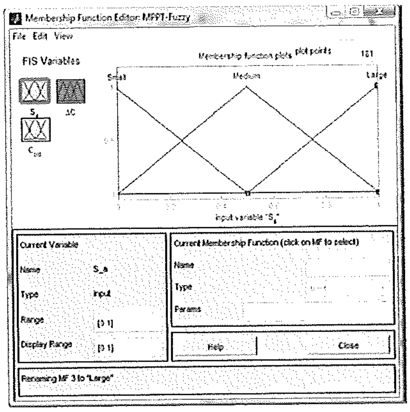


Fig. 9: MATLAB editor FIS Windows



a) S_a MF *b) C_{old} MF*



c) *ΔC MF*

***Fig. 10:** The member function editor in the MATLAB window a) S_a MF b) C_{old} MF c) ΔC MF*

The last step is to implement the FLC controller and to define the basic rules to create the input and output maps, according to **Figure 11.**

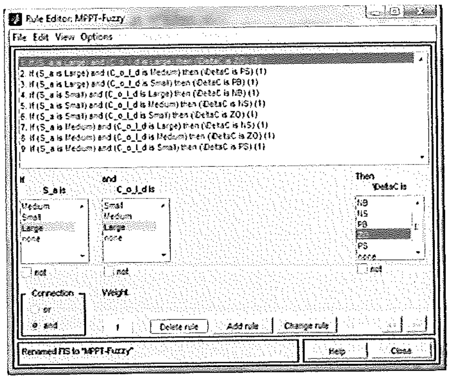


***Fig. 11:** The rules editor in the MATLAB window*

After creating the FLC controller in the MATLAB working environment, based on the P&O algorithm we made the FLC controller configuration for each component of the PV system as follows, namely: **Figure 12** shows the configuration of the MPPT based on the FLC controller with the following notations: P_{PV} is the actual power of the PV system, I_{PV} is the current in the system, V_{PV} is the system voltage, P_r is the maximum estimated reference power, and S is the signal from the FLC controller.
In the FLC algorithm implementation diagram in the MATLAB / Simulink simulation software (see **Figure 13**), the input to the FLC controller is represented by the estimated reference power (P_r) and the actual power of the PV system (P_{PV}), and the output from controller is represented by the command signal (S).

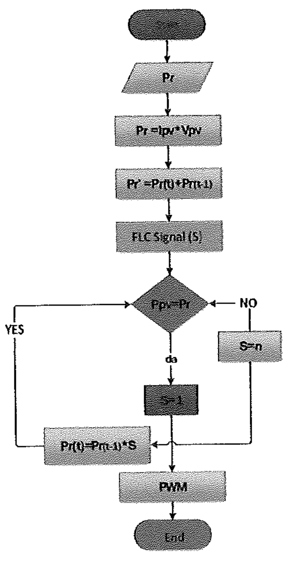


***Fig. 12:** MPPT-based FLC controller configuration*

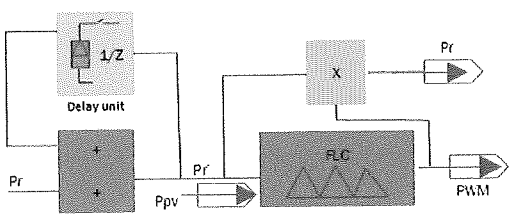
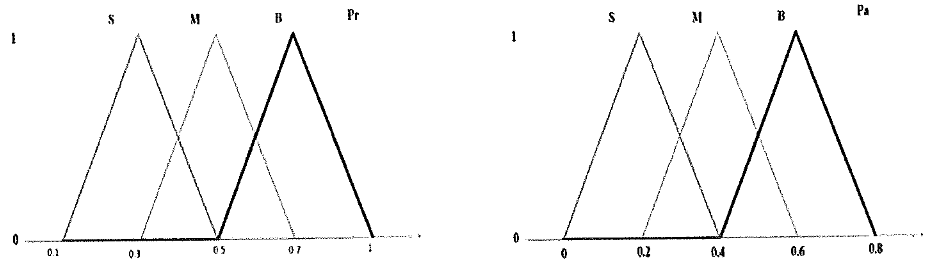


***Fig.13:** Logic diagram for implementing the control algorithm in MATLAB*

Each input variable is represented by three triangular member functions: small, medium, and high. The output variable is a singleton function with three variables. small (S) at 1, medium (M) at 5 and high (B) at 10. **Figure 14** shows the input functions for two cases: a) the reference power (P_r); b) the actual power of the system (P_{PV}) based on FLC and MPPT.



a) Entry member function Fuzzy P_r *b) Entry member function Fuzzy P_{PV}*

***Fig. 14:** FLC function for MPPT*

The purpose of the FLC controller is to force the control signal (PWM) to increase the actual power (P_{PV}) as close as possible to the maximum estimated reference power (P_r). When the actual power is much lower than the reference power, the control signal triggers the increase of the actual power. The value of the FLC output signal depends very much on the variation between the two values of P_r and P_{PV} power. Next, the Fuzzy rules are presented, indicating the meanings of the sizes of the FLC incremental algorithm.

1. If P_r is small and P_{PV} is small, then S is small
2. If P_r is medium and P_{PV} is low, then S is medium
3. If P_r is average and P_{PV} is average, then S is small
4. If P_r is high and P_{PV} is low, then S is high
5. If P_r is high and P_{PV} is medium, then S is medium
6. If P_r is high and P_{PV} is high, then S is medium

B) Configuration of the FLC for the charge battery and load

Battery charging and power transfer operations are fast-changing. For this reason, it can be said that the control operation of the battery regulator is essential for the efficiency and stability of the PV system. The operation of the battery to control the total power distribution and the operation of charging and discharging, using the FLC control algorithm can be described in the following ways:

1) Charging mode: the power in the PV generator is higher than the load requirements ($P_{PV}> P_L$). The power taken by the battery represents the difference between the two powers (P_{PV} - P_L).
2) Discharge mode: the power supplied by the PV generator is lower than the load requirements ($P_{PV} <P_L$). The battery is discharged (P_L - P_{PV}), to ensure the load, when the system can not meet the requirements of the consumer.
3) Standby mode: the load is equal to or almost equal to the power provided by the PV generator ($P_{PV} = P_L$). No need to discharge the battery.

Figure 15 shows the configuration of the FLC controller, with the following specifications: the input power to the FLC controller (P_{PV}) is the difference between the desired power (P_d) and the actual battery power (P_B). The desired power can be found in the difference between the power of the consumer (P_L) and the power of the PV generator (P_{PV}). The output signal from the controller (I') is compared to the actual battery current (I_B) after which it is directed to the PWM. PWM generates the signal that determines the operating cycle of the DC-DC converter; it changes the current to charge and discharge the battery according to the operating conditions of the PV system.
The operation of charging and discharging the battery required to simulate the complex PV system is shown in the diagram from **Figure 16**. By the control method used, the voltage, current and output power are adjusted and stabilized at the optimum load value.
Figure 17 shows the configuration of the load controller, with the following notations: (V_L) represents the actual load voltage, (V_{Ld}) represents the desired load voltage, (I") represents the reference current and (I_L) is the load current. In any load specification there are certain values of current /voltage, respectively of the power that must be supplied correctly to the load during the operation of the complex PV system. The control of voltage and load current is done by implementing an FLC algorithm based on MPPT in the MATLAB / Simulink work environment, for power control.

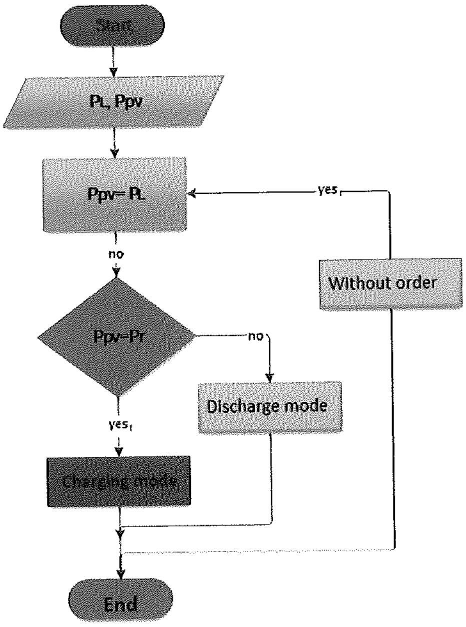


Fig. 15: Configuration of FLC controller.

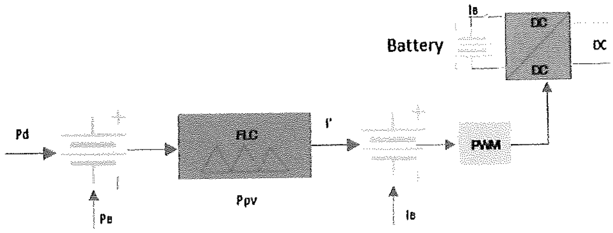


Fig. 16: Battery operation / operation logic diagram

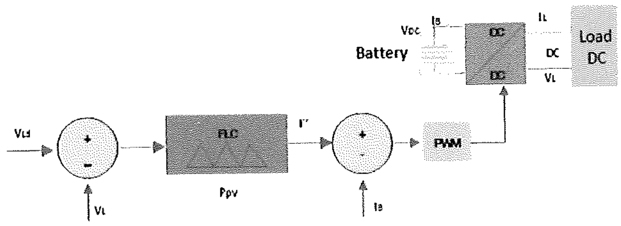


Fig. 17: Voltage regulator control diagram

4. Numerical modelling and simulation of the characteristics and performances of the PV generator. Case study

4.1 The study of the temperature and solar irradiance influence on the PV generator characteristics

In order to determine the performance of the solar cell and PV panel in the MATLAB / Simulink work environment, a numerical modeling and simulation methodology based on the block diagram presented in **Figure 18** was developed. The input data for performing the PV generator simulation are shown in **Figure 19.**

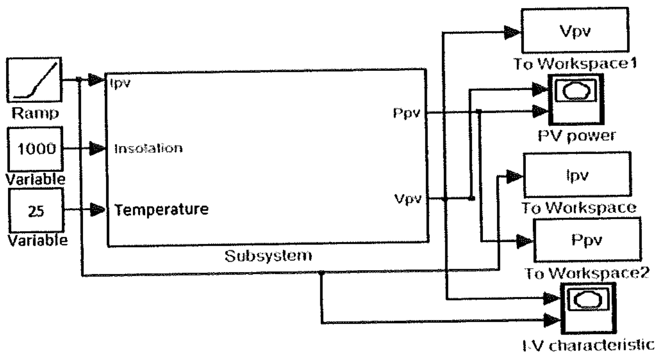


Fig. 18: PV generator test block diagram implemented in MATLAB/Simulink

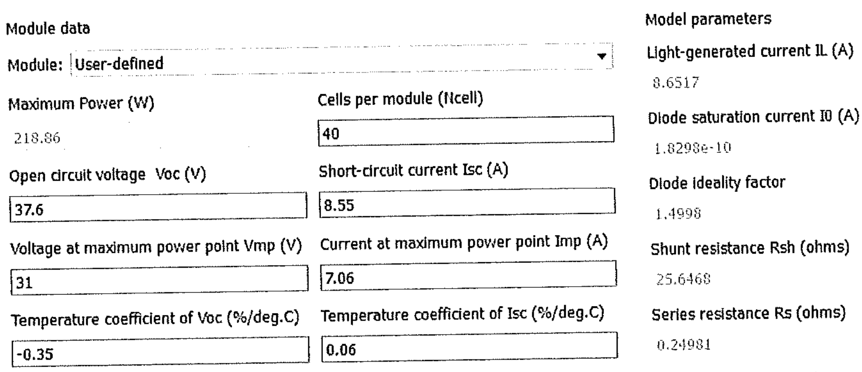


Fig. 19: PV Generator Test Interface - MATLAB / Simulink

In this section, the modeling and simulation of the solar cell and PV panel allowed to obtain its behavior for different values of temperature and solar irradiance, respectively. The current voltage (I-V) characteristic of the PV generator was determined for 1000 W /m^2 at different values of temperatures and solar irradiance in relation to the reference size represented by the red line (STC) (see **Figure 20**). In the case of the power-voltage characteristic of the PV generator, both the values of solar irradiance and temperature were varied.
The maximum power recorded by the PV panel can be seen in **Figure 21**. It can be seen that, in the case of both characteristics, the curves obtained by numerical modeling are very close to the reference curve, which indicates the accuracy of the model, respectively the accuracy of the MATLAB/Simulink working environment.

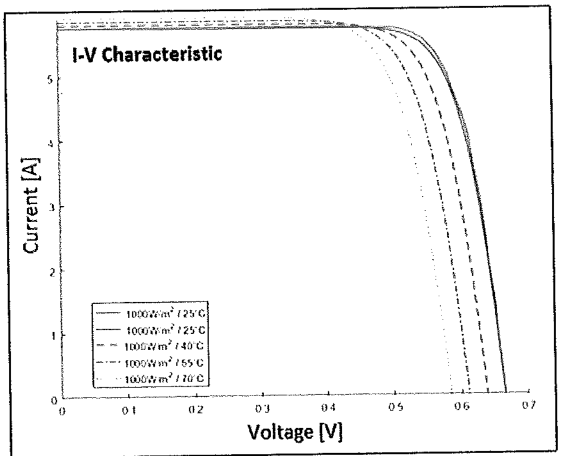


Fig. 20: Current-voltage (I-V) characteristic of the solar cell obtained with the help of MATLAB software, for different values of solar irradiance, respectively of temperature

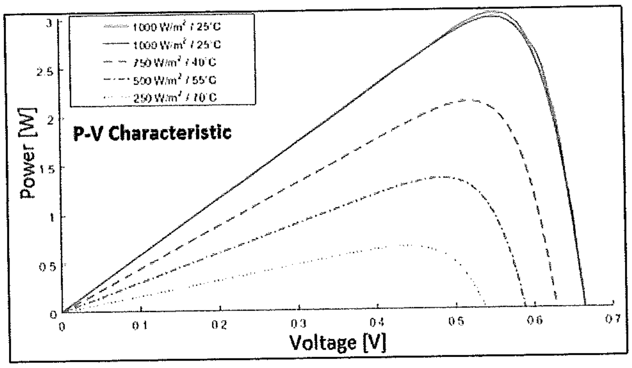


Fig. 21: Power-voltage (P-V) characteristic of the solar cell obtained with the help of the MATLAB software for different values of the solar irradiance, respectively of the temperature

The technical parameters of the PV generator were obtained from the SUNTECH manufacturer's catalog. In order to model and simulate the electrical performance of the PV generator, they used the library of the Simulink/MATLAB PV modules for its implementation and testing.

The characteristics and performances of the photovoltaic generator were analyzed for a temperature range between 20-100°C in **Figures 22** and **23**. At the same time, the characteristics and performances of the photovoltaic generator were analyzed from the point of view of the values of solar irradiance in the field 200-1000 W/m^2 in Figures 24 and 25. For a numerical simulation test as close as possible to the existing (real) panels, the total number of cells was set to be equal to 40. Based on the input sizes, respectively the block scheme implemented in MATLAB/Simulink, the output characteristics were obtained. of the PV module.

In **Figure 22**, respectively in **Figure 23**, the evolution of current and voltage, respectively power and voltage can be observed for different temperature values. With the help of the block diagram in Figure 18 it was possible to determine the values of the maximum power points associated with current and voltage (**I_{mp}** and **V_{mp}**).

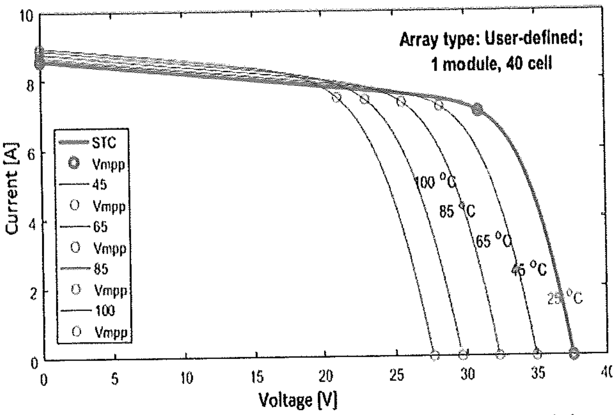


Fig. 22: The current-voltage (I-V) characteristic of the PV module obtained with the help of MATLAB / Simulink software for different temperature values

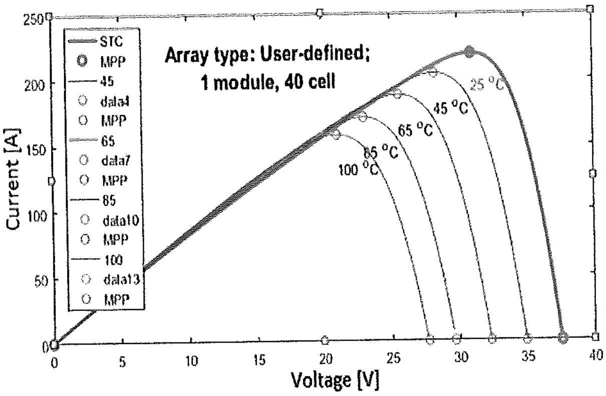


Fig. 23: Power-voltage (P-V) characteristic of the PV module obtained using MATLAB / Simulink software for different temperature values

In the same way, the output characteristics of the PV module were determined in relation to the variation of the solar irradiance, within the limits indicated in the obtained figures; we can extract from the diagram the values of the maximum power points associated with the maximum values of current and voltage (**I_{mp}** and **V_{mp}**), as seen in **Figures 24** and **25**. For the tested module (by simulation) a power was obtained maximum of approximately 219 W, a value comparable to that of existing models on the market (real). The final analysis of the PV generator is presented from the point of view of the main parameters (indicators): **I_{sc}, V_{OC}, P_{max}, FF**.

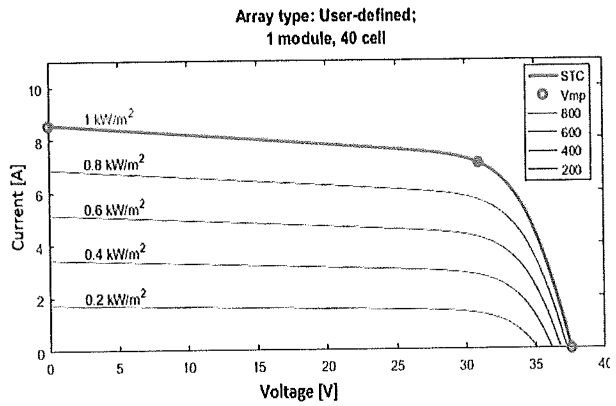


Fig. 24: The current-voltage (I-V) characteristic of the PV module obtained with the help of MATLAB / Simulink software for different values of solar irradiance

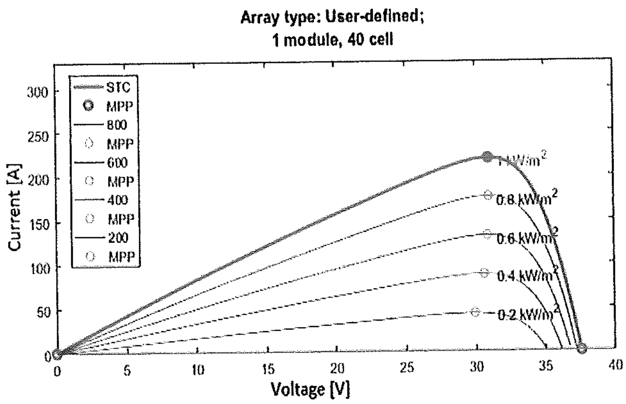


Fig. 25: Power-voltage (P-V) characteristic of the PV module obtained with the help of MATLAB / Simulink software for different values of solar irradiance

4.2. Results and discussion regarding the studied PV generator main parameters

Based on the results obtained in Table 2 (values related to the obtained characteristic curves) it was possible to determine the performance of the PV module. The graphical representation of the main parameters of the PV generator took into account the real operating conditions, where the temperature was observed in the range of 20-100°C.

It was highlighted the way in which these main parameters behave at temperature variations, namely: **1)** short circuit current **I_{sc} (Figure 26)**, **2)** open circuit voltage **V_{oc} (Figure 27)**, **3)** maximum power **P_{max} (Figure 28)**, and **4)** the filling factor **FF (Figure 29)**. This was made possible by activating a function in the model that allows the random generation of temperature in order to simulate the real operating conditions of the PV generator.

Table 2: *The main parameters of the studied PV generator*

T_{env}	I_{sc}	V_{oc}	P_{max}	FF
°C	A	V	W	-
20	8.5537	37.60	218.86	75.47
25	8.4796	37.45	197.64	74.98
30	8.3578	36.87	194.94	74.02
35	8.3222	35.87	190.91	73.60
40	8.2754	35.00	187.67	72.29
45	8.2466	34.12	176.65	72.03
50	8.2185	33.84	172.27	71.26
55	8.2075	33.05	170.11	71.05
60	8.1917	32.53	168.94	70.25
75	8.1810	29.12	162.12	69.06
80	8.1267	28.69	160.71	68.18
85	8.0916	28.03	158.39	67.47
90	8.0887	27.59	155.32	66.31
95	8.0472	27.02	152.89	65.45

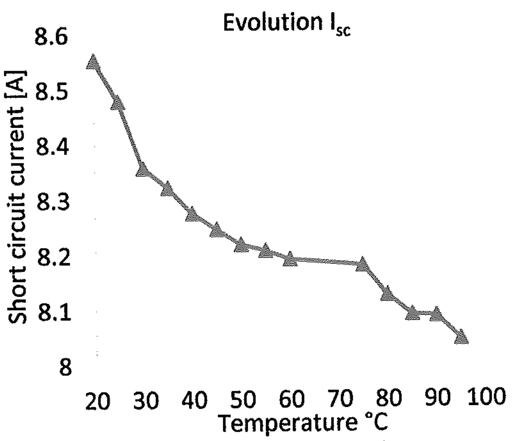


Fig.26: *Graphical representation of the short-circuit current on temperature*

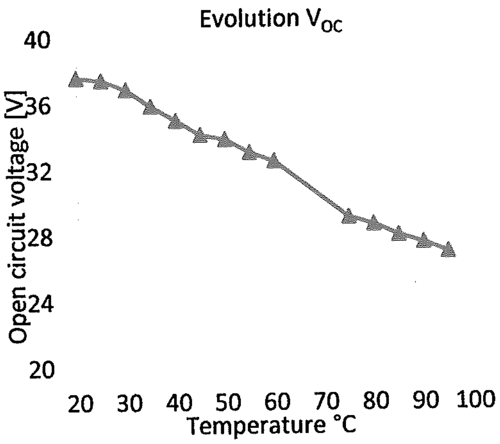


Fig. 27: *Graphical representation of the open circuit voltage on temperature*

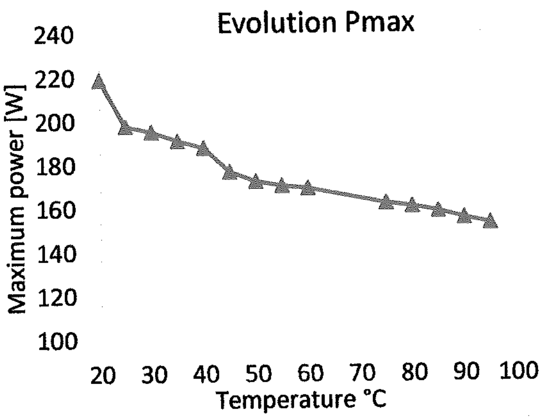


Fig. 28: *Graphical representation of the power on temperature*

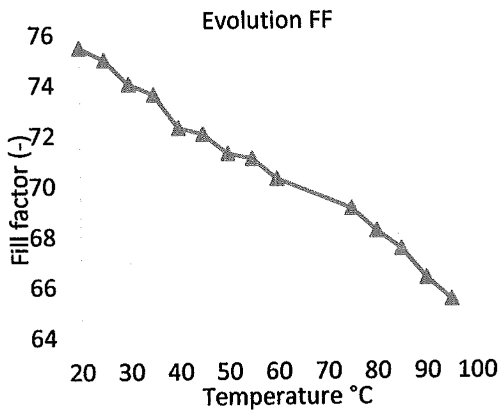


Fig. 29: *Graphical representation of the filling factor on temperature*

5. Operational optimization of the PV system based on FLC benefit. Novelty results and discussions

Following the simulations performed with the MATLAB/Simulink software and the MPPT based on FLC algorithms, interesting results were obtained regarding the behavior and performance of the studied PV system. The block diagram specific to the stand-alone (autonomous) photovoltaic system is presented in **Figure 30** and includes the following elements of BOS (battery, controller, inverter), respectively PV generator, and load. The modeling and simulation of the behavior of the photovoltaic system is based on the block elements of the considered PV system. In the following, the Fuzzy Logic Controller, MPPT and storage system (battery) will be presented and analyzed separately in order to determine their performances.

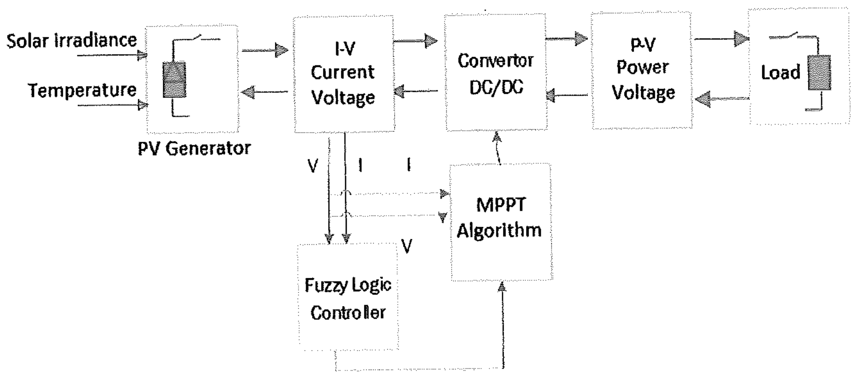


Fig.30: *Block diagram of the autonomous photovoltaic system*

The results obtained from the modeling and simulation in the MATLAB / Simulink working environment of the FLC controller based on MPPT show an increase in, both the power of the PV generator, and the power developed by the storage system (batteries). These findings are graphically represented from the point of view of the power of the PV system, the power being a decisive parameter in determining the respective efficiency and performance of the systems based on the production of electricity. In order to highlight the contribution of FLC - MPPT in relation to the simple version of MPPT in which photovoltaic systems usually work, the authors of the study made a series of comparisons designed to assess the performance of the PV system, as follows:

Figure 31 shows the power behavior of the photovoltaic generator. We can see that the maximum value of the power is around 225 W using the "simple" MPPT technique at a temperature of 20^0 C and a solar irradiance of $1000W/m^2$. If we analyze **Figure 32** we can see that after using the FLC controller based on MPPT the power value of the PV generator rises to a maximum value (peak) of about 260 W.

We can conclude that the PV generator is able to produce a surplus of power in different meteorological conditions that are fluctuating and disruptive for the PV system. For an adequate visual analysis in **Figure 33** the comparison between MPPT and MPPT - FLC is highlighted with emphasis on the power gain in the case of the PV generator.

In general, photovoltaic systems have energy storage systems with battery. Given this aspect, it is critical that the performance analysis is not limited to the PV generator, which is why the authors studied in the same way (as the PV generator) the analysis of the behavior and performance of the storage system based on MPPT and FLC-MPPT. Thus, in **Figure 34** and **Figure 35**, respectively the performance trend is similar to that recorded in the case of the PV generator. In this case a surplus of approximately 50 W was registered.

The values for the two cases are: 1) simple MPPT, the maximum registered value of the power reached the value of approximately 190 W, and 2) MPPT – FLC, the maximum value of power was around 150 W. Similarly, in the case of the PV generator in **Figure 36** is highlighted the comparison between MPPT and MPPT - FLC with emphasis on the power gain recorded by the storage system (batteries). **Figure 37** addresses in a unifying manner, both the PV generator, and the storage system, thus determining the overall performance of the photovoltaic system. We can conclude that the MPPT-based FLC extracts a power of about 260 Wp, while the only MPPT produces about 225 Wp. This means that the fuzzy controller contributes about 10% more power than the MPPT under the same conditions to charge the batteries.

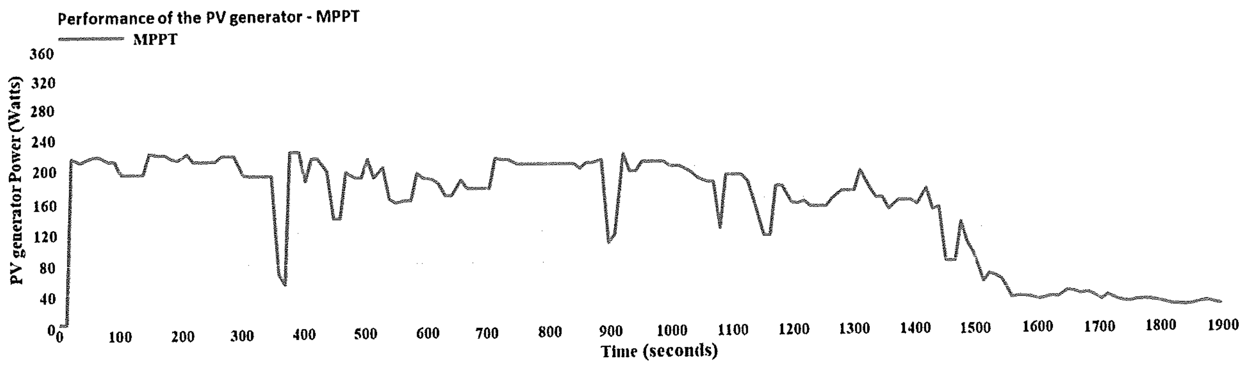


Fig.31: The performance of the PV generator based on MPPT

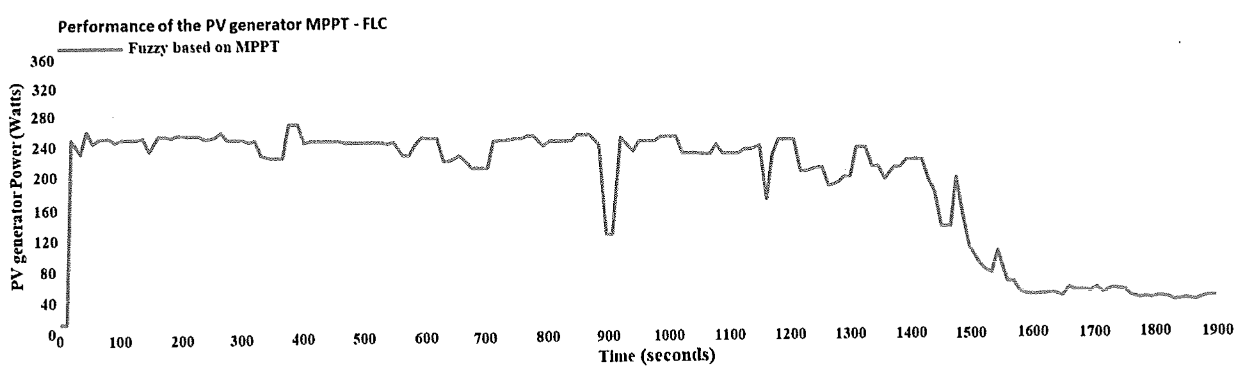


Fig.32: The performance of the PV generator based on MPPT – FLC

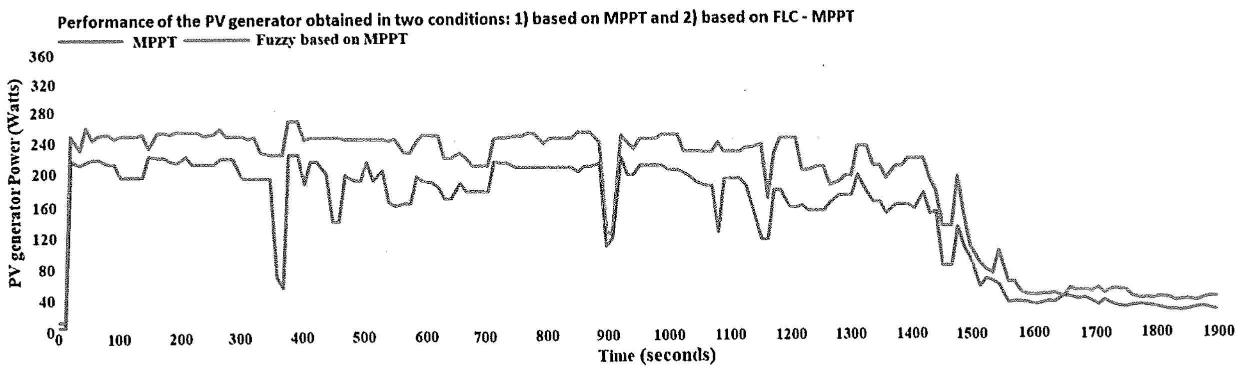


***Fig.33:** Comparison between MPPT and MPPT – FLC in terms of power gain (PV generator)*

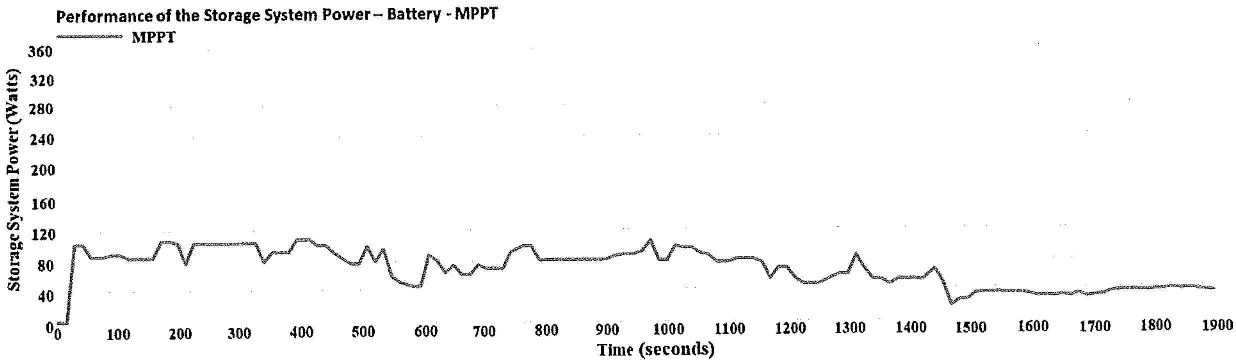


***Fig.34:** The performance of the storage system (battery) based on MPPT*

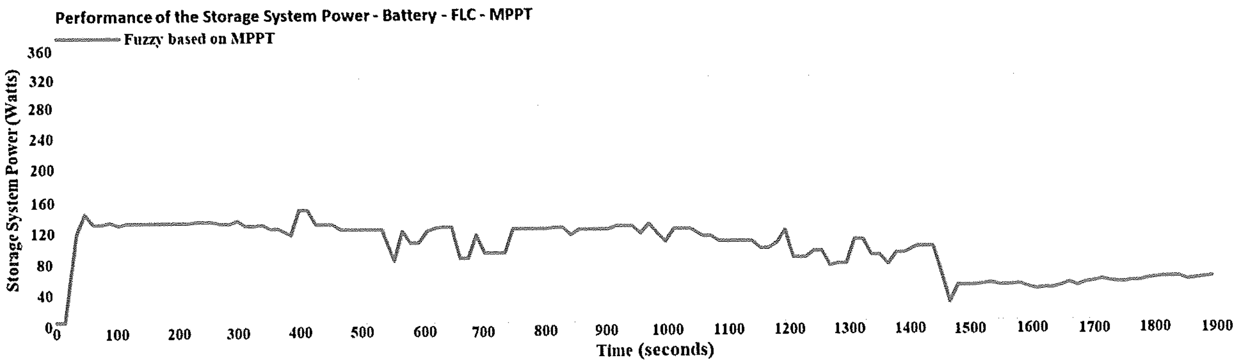


***Fig.35:** The performance of the storage system (battery) based on MPPT – FLC*

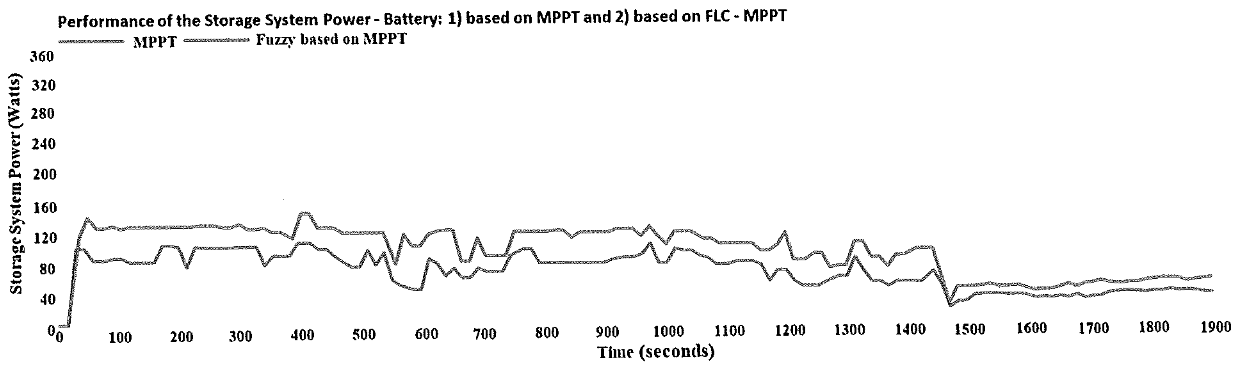


***Fig.36:** Comparison between MPPT and MPPT – FLC in terms of power gain (storage system - battery)*

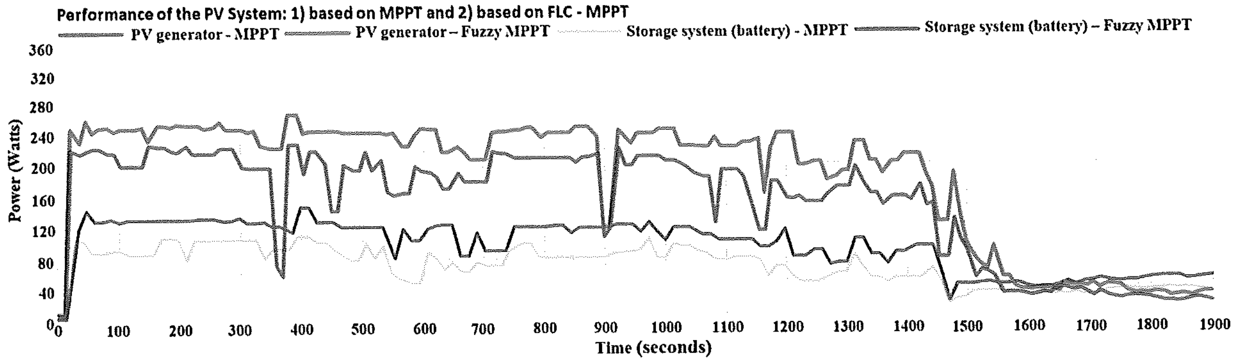


Fig.37: *Comparison between MPPT and MPPT – FLC in terms of power gain for whole PV system*

5. Conclusions

We have proposed an innovative method of optimizing photovoltaic systems, which uses a MPPT-based FLC controller to improve the efficiency of electrical output parameters, able to respond appropriately to sudden variations in solar radiation. We analyzed the influence that the FLC controller has on the output power of the photovoltaic system. In this way we managed to stabilize and improve the output parameters of the photovoltaic system in terms of safety in power supply of the load. The obtained results can be developed and widely applied, both for complex stand-alone photovoltaic systems and on-grid. The main purpose of this research was to devise an approach to extracting the maximum power from a PV system. To this end, the authors modeled the PV generator for determining and tracking the maximum power point, along with operational optimization based on the MPPT-FLC controller. Specifically, the authors modeled and simulated a reference PV system based on fuzzy logic for tracking optimal power.

The results show that a significant amount of additional energy can be extracted from a photovoltaic generator by applying a "tracker" to "track" the maximum power point based on fuzzy logic. At the same time, these results indicate an improved efficiency of the PV system, as the batteries can then be charged and used during periods of low solar radiation.

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Abbreviations:

PV	– Photovoltaic	GA	– Genetic Algorithm
MPPT	– Maximum Power Point Tracking	ACO	– Ant Colony
AC	– Alternative Current	PSO	– Particle Swarm
DC	– Direct Current	ANFIS	– Adaptive Neuron Fuzzy Inference system
I-V	– Current-Voltage characteristics	ML	– Machine Learning
P-V	– Power-Voltage characteristics	AI	– Artificial Intelligence
FLC	– Fuzzy Logic Controller	DT	– Digital Twin
FIS	– Fuzzy Inference System	Io T	– Internet of Things
NN	– Neural Network	nZEB	– nearly Zero Energy Building
FL	– Fuzzy Logic	C_{old}	– old disturbance
SA	– Simulated Annealing	IRENA	– International Renewable Energy Agency
MF	-Member Function	P_r	-reference power
NB	-Large Negative	P_{PV}	-actual power
NS	-Low Negative	P_L	-consumer power
PS	-Small Positive	W_p	-watt peak
PB	-Large Positive	ANN	-Artificial Neural Network
ZO	-Zero	Sa	-slope
ΔC	-Exit membership	PWM	-Pulse Width Modulation
S	-command signal	FF	-filling factor
I_{sc}	-short circuit current	I_B	-battery current
V_{oc}	-open circuit voltage	V_{Ld}	-actual load voltage
P_{max}	-maximum power	I_L	-load current
I"	-reference current	BOS	-Balance Of System

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