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COMPREHENSIVE REVIEW OF MAXIMUM POWER POINT TRACKING TECHNIQUES AND PROPOSED FUZZY LOGIC CONTROLLER OF AN ELECTRICAL POWER SYSTEM FOR NANO SATELLITES

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This paper's research focuses on areas related to the electrical power system (EPS) used for nanosatellite platforms with an adapted electrical architecture and an effective control strategy. An overview of the relevant maximum power point tracking (MPPT) algorithms is presented towards proposing a more suitable control technique. The main contribution of this research is the implementation of a novel fuzzy logic control (FLC) strategy, which significantly reduces ripples around Maximum Power Point (MPP) improving both the efficiency and the flexibility of convergence, and the response time as well. A comparative study and analysis are presented to demonstrate the performance and the effectiveness of the proposed FLC. The assessment is performed in comparison between the most common methods (perturb and observe (P&O) and Incremental Conductance (INC)) used for MPPT. The results obtained are very substantial and show that the proposed FLC technique, with regard to the other techniques discussed in this paper, points to the extraction of the highest and most stable amount of average power under different space environmental conditions.

1. INTRODUCTION

Over 400 CubeSats have been successfully launched by the end of 2015, a rapidly growing field since the CubeSat standard was introduced in 1999 [1]. A CubeSat is a Nano-Satellite that comprises one or more units of 10 cm × 10 cm × 10 cm based on commercial-on-the-shelf (COTS) components, with a standardized mechanical interface for a launch adaptor and comprises one or more units of 10 cm × 10 cm × 10 cm.

A continuous operation throughout the desired Nano-Satellite mission lays critically on its energy sources. The satellite power budget is defined to support the payload and the platform over the mission lifetime and beyond; this need to provide an adequate Electrical Power System (EPS) architecture, which has, the EPS, to guarantee the following main functions: energy harvesting, energy conversion, energy storage, power conditioning, and power distribution. Over 25% of spacecraft in-orbit failures are due to EPS failures; it is a major factor affecting the reliability of the spacecraft [2]. Accordingly, researchers and satellite manufacturers work side by side towards a more reliable design by using improved testing procedures, and by maximizing control techniques' efficiency [3].

EPS architectures of a satellite power bus are mainly DET (direct energy transfer) method and the PPT (peak power tracking) method [1], all other architectures are a combination of them.

In DET, the exact amount of required power is directly transferred to the loads without power converters. However, the majority of nano-satellites missions using the DET topology have an efficiency loss due to a dissipation function [4].

For PPT architecture, the power is transferred to the main bus by dc/dc power, which is controlled as a function of the required bus power demand by setting the solar array operating at a point that allows the maximum power transfer from the solar arrays to the loads.

Unlike the DET, the PPT allows to eliminating the thermal dissipation problems and increasing the power system efficiency [5]. It is considered a non-dissipative circuit [6] since it can also increase the solar array's maximum power amount. The PPT technique is more suitable for low earth orbit "LEO" satellites having relatively short sunlight periods [7], as well as for low-power missions under 5 years that require more power at BOL than at EOL [8,9].

MPPT algorithms used for PPT systems in space applications are quite similar to those used in-ground applications. A number of studies focused on the development of MPPT's algorithms are presented in the literature, such as: perturb and observe (P&O) [10] incremental conductance (INC) [11] and so-called intelligent control based on Fuzzy Logic (FL) [12]. However, the development of adaptive and artificial intelligence techniques to increase the efficiency of the PV system remains a challenging research field nowadays. Some algorithms based on intelligent techniques such as FL [13,14] and the adaptive neural-fuzzy inference system (ANFIS) [15] have been improved and developed.

As explained in [16-18], FL control techniques are appropriate for non-linear control and make it possible to effectively operate and manipulate linguistic information emanating from human expertise through an important theoretical foundation.

Fuzzy logic controllers (FLCs) are able to use professional acquaintance or experimental methods to adjust the output control system even without understanding the mathematical model of the systems being controlled, unlike traditional controllers such as P&O and INC. In [19], the implementation of FLC based on power variation and output voltage variation is studied. Where, in [20], an optimal asymmetrical FLC-based MPPT is presented, in this research, no proportional or integral control loop exists and the control signals are generated by adaptive FLC. In order to improve the transient time and the MPP tracking accuracy, [21] presented a simulation and hardware implementation of MPPT based on FL using the particle swarm optimization technique. Whereas in [22], an MPPT scheme based on a fuzzy approach is proposed, the optimization is achieved by accurately tracking the MPPs

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of the PV system.

This paper focuses on designing the EPS architecture for nanosatellites with an appropriate control algorithm that ensures maximum power extraction. To achieve this aim, an overview of MPPT control techniques is first given aimed to compare the most suitable MPPT control techniques for space applications. Then, an MPPT control method based on a novel FLC strategy is proposed and presented.

The rest of the paper is organized as follows: the EPS architecture and modeling are presented in section 2. Section 3 is devoted to reviewing the most popular MPPT techniques with general operating principles. Then, the design of the proposed fuzzy control strategy for the MPPT technique is described in section 4. Simulations are conducted for different irradiance and temperature conditions; the results obtained are presented in section 5 to prove the effectiveness of the proposed FLC strategy. A discussion of the results obtained from the proposed study is presented in the conclusion.

2. **EPS MODELING ARCHITECTURE**

The proposed EPS architecture is shown in Fig. 1. The solar panels are mounted on five sides of the Nano-Satellite; each pair of solar panels are connected to one boost converter, leading to three converters in total. Each two opposite facet solar panels are connected to the same power converter as follows: (–X array and +X array are connected to MPPT1, -Y and +Y to MPPT2, and –Z to MPPT3). The power converters are coupled in parallel and each converter has an implemented algorithm for MPPT. In the proposed configuration, just one panel per pair can be illuminated by the sunlight, whereas, the second panel provides a partial amount of energy due to albedo illumination from the earth.

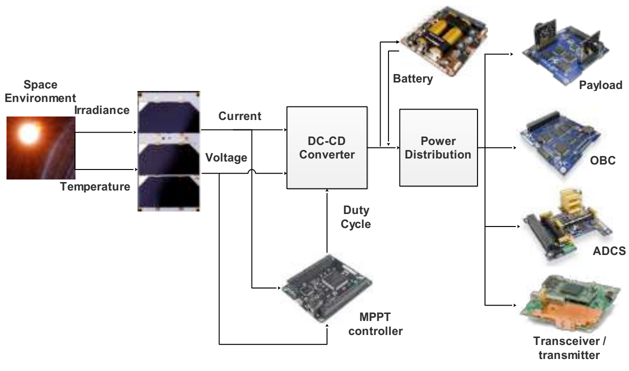


Fig. 1 – EPS based on PPT circuit.

2.1. SOLAR PANEL MODELING

Generally, the efficient photovoltaic solar cell technology based on triple-junction cells is more suitable for Nano-Satellite applications to extract the maximum sunlight power. This technology consists of the deposition of different semiconductors layers, forming multiple sub-cells, each of which has its own PN junction form and gap. Each sub-cell responds to a spectral band according to its semiconductor materials. The sub-cells are divided by tunnel junctions, which permit the current flow between them [23].

The triple-junction solar cell circuit model (Fig. 2) is obtained from the series connection of the single diode model. This model presents several diodes that describe the saturation current [24].

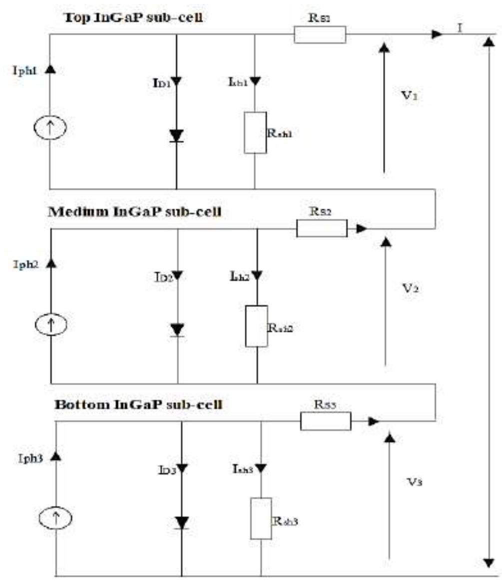


Fig. 2 – Circuit model of triple-junction solar cell.

The mathematical expression of the current generated by each solar cell junction is presented by the following equations:

$$I_i = I_{ph,i} - I_{0,i}\left(\mathrm{e}^{\frac{q\left(V_i - I_i\, R_{S,i}\right)}{n_i\, K\, T}} - 1\right) - \frac{V_i - I_i\, R_{S,i}}{R_{SH,i}} . \tag{1}$$

Where I_i is the current of the solar cell junction, $I_{ph,i}$ is the photocurrent of the solar cell junction, $I_{0,i}$ is the inverse saturation current of the diode of the solar cell junction, where $R_{S,i}$ and $R_{SH,i}$ are the series and shunt resistances of the cell junction, respectively; V_i is the total voltage across the cell junction. K, q, n_i, and T are, respectively: the Boltzmann constant, the electron charge, the ideality factor of the diode, and the temperature of the solar cell junction. The expressions of the diode saturation current and energy band-gap are presented as follows:

$$I_{0,i} = K_i\, T^{\left(3+\frac{\gamma_i}{2}\right)} e^{\frac{-E_{g,i}}{n_i K T}} , \tag{2}$$

$$E_{g,i} = E_{g,i}(0) - \frac{\alpha_i T_c^2}{T + \beta_i} . \tag{3}$$

The total generated current due to the series connection is given by the minimum generated current of the three solar cell junctions [25]:

$$I = \min\left(I_1, I_2, I_3\right) . \tag{4}$$

The total generated voltage is the sum of the generated voltage in each solar cell junction, henceforth:

$$V = \sum_{i=1}^{3} V_i . \tag{5}$$

In practical applications, according to [26], the one-diode model is suitable for defining the physical characteristics of the triple-junction solar cell. This equivalent model has a source of current, a diode, a series, and a shunt resistor, representing the same system losses obtained by the triple-junction solar cell [23]. The current generated by the solar cell is expressed as follows:

$$I = I_{ph} - I_0 \left(e^{q\left(\frac{V + IR_s}{nKT}\right)} - 1 \right) - \frac{V + IR_s}{R_{SH}}, \qquad (6)$$

where, I_{ph} and I_0 are the current sources and the saturation current of the diode respectively.

The solar cells used in this model are based on AZURSPACE technology, which parameters are presented in the datasheet [27].

2.2. POWER CONVERTER

The dynamic model of the boost DC-DC converter is obtained by the application of basic Kirchhoff laws, as written in the following state equation form

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} I_l \\ V_{dc2} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C_2} & -\frac{1}{C_2 R} \end{bmatrix}\begin{bmatrix} I_l \\ V_{dc2} \end{bmatrix} + \begin{bmatrix} \frac{V_{dc2}}{L} \\ \frac{I_l}{C_2} \end{bmatrix} U + \begin{bmatrix} \frac{V_{pv}}{L} \\ 0 \end{bmatrix}, \qquad (7)$$

where V_{pv} is the voltage of PV panel, V_{dc2} and $I_{load} = {V_{dc2}}/{R}$ are the output voltage and load current, respectively. The control input $U \in \{0,1\}$ is the switching function.

3. **COMPREHENSIVE REVIEW OF MPPT TECHNIQUES**

The MPPT algorithm aims is to follow the maximum power point of a PV system; whereas, the maximum possible current depends on the received solar irradiance. Therefore, to increase the power, only the voltage can be varied. This variation can be controlled using a dc-dc converter while acting on it. Specific and well-defined algorithms ensure this automatic and sometimes intelligent duty cycle variation. In this section, an overview of the most popular categories of MPPT algorithms is presented in Fig. 3.

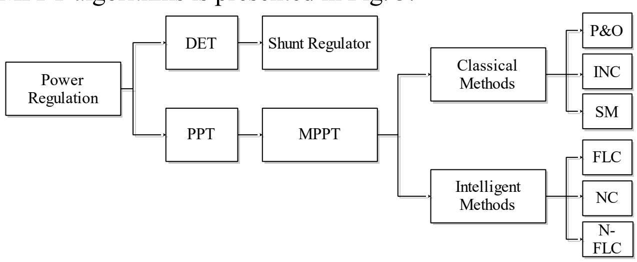


Fig. 3 – Categories of power regulation techniques based on MPPT algorithms [28].

3.1. PERTURB AND OBSERVE ‘P&O’ METHOD

The Perturb and observe method is the most common technique used in photovoltaic systems [29] as its algorithm is easy to implement [30]. Many research papers proposed improvements for the P&O algorithm to reduce the steady-state oscillation and increase the efficiency of the MPPT such as in [31]. In [32] the modification brought in the P&O algorithm was to add the change in PV current as a third test which increases the convergence speed and improves the average efficiency by 4% during solar irradiance variations.

The P&O method aims to stay as close as possible to the Maximum Power Point (MPP). This method is based on the generation of a periodic disturbance in the PV panel voltage, whose direction, positive or negative, will be a function of the previous output power value, then observing its effect on the output power obtained at the current time. If the power measured at the current instant is greater than that measured at the previous instant, the power is approaching the MPP. Therefore, this voltage disturbance is done with a different algebraic sign to the preceding one to continue changing the operating point until reaching the MPP.

3.2. INCREMENTAL CONDUCTANCE ‘INC’ METHOD

Among the MPPT methods, the INC algorithm is largely used due to its simple implementation and high tracking accuracy. It was firstly developed by [33]; then, the dynamic and the tracking of this method has been proven to be better than the ‘P&O’ method under rapidly changing atmospheric conditions [34]. However, the digital implementation of the algorithm leads to an error on the “decision of maximum power operation point”; to solve this issue, [57] proposed to insert a test signal in the control input to improve the incremental conductance algorithm that is determining the maximum power point under rapidly changing solar radiation condition.

In [35], a modified variable the step size of the INC algorithm is proposed to automatically adjust step size for MPP tracking. This INC control method has been carried out with the introduction of a simple Constant Voltage Tracking (CVT) to allow the smoothness of the startup process and simultaneously improve the response time and the accuracy of the system.

The INC method consists of measuring the changes in the current and voltage of the PV array, the MPP is reached when $\mathrm{d}P/\mathrm{d}V = 0$.

Once the MPP is reached, the disruption process stops and only starts again when $\mathrm{d}I/\mathrm{d}V$ is below or above $-I/V$.

3.3. FUZZY LOGIC ‘FL’ METHOD

The FLC was first introduced in [36] for MPPT application, where, the authors aimed to tackle the commonly known issues in the ‘P&O’ and ‘INC’ algorithms, such as the trade-off between response time and steady-state oscillations. In [20], the implementation of an optimal asymmetrical FLC based on the power variation and the output voltage variation is studied. In addition, to improve the performance of the proposed technique, an asymmetric membership function concept is also proposed; then, two additional design procedures are proposed to determine the universe of discourse for the inputs. This method can significantly improve transient time and MPPT tracking accuracy. In [22], an MPPT scheme is proposed based on a fuzzy approach. The optimization is achieved in tracking the MPP of the PV system by a boost-converter using an “antecedent-consequent adaptive” indirect fuzzy-based MPPT scheme, which is adjusted online using a novel computationally light membership function tuning routine, where the membership functions are tuned synchronously. A novel beta parameter three-input one-output fuzzy-logic based MPPT algorithm is presented in

[37] for photovoltaic systems. A third input "an intermediate variable β" is introduced to reduce the dependency of the user's knowledge on the system; this input simplifies the fuzzy rule membership and functions and covers wider operating conditions.

The design of the FL system requires passing through the fuzzy parameter selection steps, membership functions, inference methods, and Fuzzification strategy. The most common FL MPPT algorithms are based on the fuzzy input variables from the PV system voltage and current signals. The fuzzy input variables would therefore be used to calculate the duty cycle to adjust the operating point of the photovoltaic system.

3.4. NEURAL NETWORK-BASED MPPT METHOD

Over the last few decades, intelligent control approaches such as Neural Networks (NN) and fuzzy logic have been successfully used in several applications. Excellent performance can be achieved by combining NN and fuzzy techniques for solar PV MPPT, but the high computational load has limited the use of this hybrid technique [38]. The logic of the neural network is motivated by the sophisticated functionality of the human brain where hundreds of billions of interconnected neurons process information in parallel. Thus, neural networks based on MPPT are generally presented as systems of interconnected "neurons" that send messages to each other. For example, any of the solar array parameters, like open-circuit voltage and short-circuit current, irradiance, temperature, or any combination of them, can be taken as the input variables for the neural network. In general, three layers are used in neural networks that are: the input layer, the hidden layer, and the output layer. A faster operation can be achieved by using two-stage ANN with Incremental Conductance MPPT, but this requires a sophisticated system to supervise the control and the switch between the two stages [39,40]. A duty cycle is an output signal used to control the power converter to operate the PV system at its MPP or close to. The precision of NN-based MPPT depends on its training as well as the algorithm used in the hidden layer. The number of training sets can be reduced by using two cascaded NNs [40]. These patterns differ depending on the PV array used, as most of them have their specific characteristics; thus, the neural network has to be specially trained according to the used PV array. In addition, since the PV array characteristics changes during their lifetime, a periodic training of the neural network is recommended.

3.5. HYBRID METHODS

The application of the hybrid MPPT method consists of using a combination of two or more MPPT techniques to increase the tracking performance. A considerable number of research studies have been done on the hybrid techniques, the most common are P&O-based hybrid MPPT. In [41], an intelligent ANN-P&O MPPT controller uses both ANN and P&O techniques to improve the conversion efficiency of the PV system. In [42], ANN optimization was used in conjunction with INC/P&O MPPT to vary the duty cycle, and achieve quick follow-up with a smaller steady-state error. In [43], Fuzzy Logic with ANN in hybrid MPPT was used. In [44], an indirect hybrid fuzzy-P&O variable step size MPPT controller is studied to improve the tracking performance under fast-changing conditions. Further hybrid techniques have been studied and proposed through literature [45,46].

3.6. OTHER MPPT METHODS

In [47], a proposed modified fractional open-circuit voltage technique, which is an MPPT technique based on the roughly linear relationship between the voltage at MPP (V_{MPP}) and the open-circuit voltage (V_{oc}) of the PV solar panel under varying irradiance and temperature levels. [48] showed that controlling MPPTs via their output parameters can be done regardless of load nature; this technique facilitates the measurement of the output parameter without using a multiplier in the controller. In [49], several Distributed MPPT (DMPPT) methods have been presented based on the use of a separate MPPT for each element in DMPPT. In [50], a method called "a state-based MPPT" is used to follow the MPPs by a nonlinear time varying dynamic feedback controller. A different alternative is presented in [51], where an MPPT method maximizes the output power of the PV module by calculating it's the current and the voltage using irradiance and temperature. [52] proposed an MPPT method based on statistical data collection of irradiance and temperature levels for one year; the data are used for MPPs characterization and to control the power converter to the desired voltage level. In [53], a linear-reoriented coordinates MPPT method is presented, where an estimated solution of the PV array equation is obtained iteratively. In this linear coordinate reorientation method, a PI controller uses the linear relationship between the current at the MPP and the irradiance level.

3.7. COMMON MPPT TECHNIQUES FOR NANO-SATELLITE'S EPS

The MPPT techniques used for space applications are similar to those used for terrestrial ones; however, it is necessary to adapt them to the rapid changes in space environmental conditions. Only a few studies revealed their algorithms used onboard satellites, all based on one of the techniques previously presented [9]. Hill Climbing (HC) technique is applied for space applications in MPPT controllers due to its precision, simple structure, and independence from sensors such as irradiance and temperature sensors [54]. However, this method has three major disadvantages, firstly: local peaks tracking on the solar array P(V) curve, secondly: oscillations behavior around the MPP, and thirdly: low response time [54]. Regarding the FLC-based MPPT technique, it has been introduced in the field of Nano-Satellite, where many FLC variants for MPPT have been proposed through research studies, such as [55,56].

Based on the previous studies, this paper presents an improved FLC technique, then compared it with the two other techniques, P&O and INC, in terms of rapidity, stability, and adaptability for space applications. This proposed technique will be discussed in the following section.

4. **PROPOSED FUZZY LOGIC CONTROL STRATEGY**

The design of the FL MPPT technique varies according to the input and output variables parameters, which introduces diverse effects on the MPPT process. The output variable is frequently the duty cycle of the DC-DC converter. However, the most usually used input variables are based on the electrical characteristics of the PV system. For example, [57] used the power and corresponding voltage (P,V) as input variables, and [37,58] used the errors $E(P,V)$ and the error variations ΔE of the PV system instead. Other studies selected as input variables the power and voltage variations ΔP & ΔV [20,59] or the power and the current variations ΔP & ΔI [18]. Nevertheless, of all these combinations, few studies have investigated the duty cycle variation as a fuzzy input variable. However, considering this parameter, makes it possible to know effectively whether the duty cycle is located relative to the MPP. Therefore, in this paper, a novel efficient FLC-MPPT technique is proposed to automatically and intelligently adjust the duty cycle which can also improve the efficiency of the PV system.

In fact, in the proposed FLC, the input variables are the duty cycle at an instant (K-1) and the variation of the PV system output power; whereas, the output is the estimated duty cycle using the defuzzification approach. The Fig. 4 shows the flowchart of the proposed fuzzy controller calculation process.

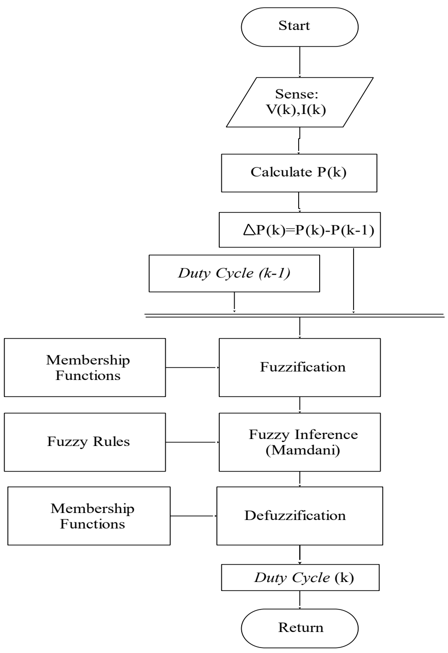


Fig. 4 – Flowchart of the proposed FLC algorithm.

The fuzzification strategy is influenced by the membership functions forms and their arrangement on the universe of discourse. Numerous membership functions can be selected: triangular, trapezoid, singleton, sigmoid, Gaussian, etc. According to the experimental results conducted in [60], the three membership functions (triangular, trapezoid, and Gaussian) offer quite similar good results, hence, the triangular one (the selected technique in this study) is the most used due to its ease implementation and robustness [5]. For the inference process, the adopted method is based on the Mamdani technique [61]; the maximum calculation performs the 'OR' operator, whereas the minimum one performs the 'AND' operator. The Centre of Gravity Method (COG) is used for defuzzification. This method makes it possible to express analytically the outputs of the FL system, to reduce the computation time, and facilitate the implementation process, which is why it is more often used. Furthermore, the COG avoids discontinuities occurrences at the defuzzification, unlike other methods especially the Mean of Maximums (MM) method [62].

$$x_S = \frac{\int_x u_\beta(x).x dx}{\int_x u_\beta(x) dx}, \tag{8}$$

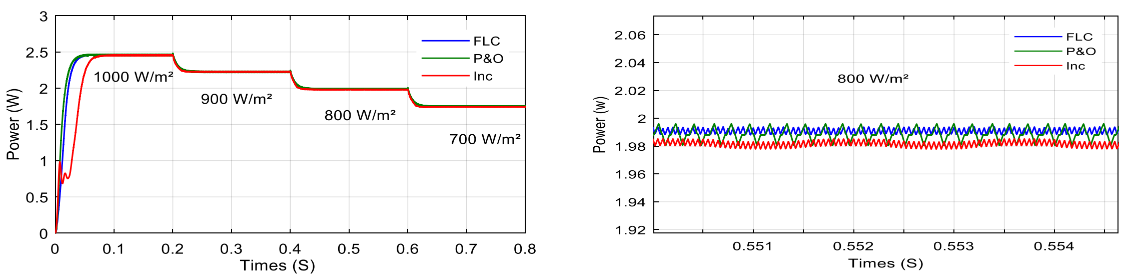
where, $u_\beta(x)$ is the membership function and x_S is the exact value of the FLC output.

5. RESULTS AND DISCUSSION

The results obtained by simulations are presented and discussed based on the implementations of the different test conditions. First, the irradiance is varied (1000 W/m², 900 W/m², 800 W/m² and 700 W/m²) while keeping a fixed temperature level (35 °C). Afterward, the temperature is varied (20 °C, 40 °C, 60 °C and 80 °C) while keeping a fixed irradiance level (1000 W/m²). Then, in order to get closer to the real orbital conditions, the MPPT based on the improved FLC controller is tested again under both irradiance and temperature variations. The power ripples around the MPP generated by the three control strategies (P&O, INC and FLC) are compared in the concluding section of this section for efficiency purposes.

5.1. IRRADIANCE VARIATION

This test aims to point out the proposed control strategy's advantages in terms of MPPs tracking and power quality compared to other control techniques at different irradiance levels (1000W/m^2, 900W/m^2, 800W/m^2 and 700W/m^2).



(a) (b)

Fig. 5 – Output powers obtained by different MPPT algorithms: (a) at different levels of irradiance; (b) Zoom at 800 W/m².

Figure 5 (a), shows that the powers obtained by using the three MPPT control methods successfully tracked their

MPPs during irradiance changes. According to this figure, at the irradiance of 1000W/m^2, the values of PV power generated by FLC, P&O and INC MPPT approaches are 2.461 W, 2.455 W and 2.45 W, respectively. At the same irradiance (1000W/m^2), the settling times for FLC, P&O and INC MPPT methods are 71.74 ms, 65.26 ms and 108.3 ms, respectively. Therefore, compared to other MPPT techniques, it can be noticed that the proposed FLC method gives a slightly higher amount of power. However, the settling time obtained by the INC method is comparatively slow and can cause larger oscillations around the MPP than the other techniques. Maximum overshoot is defined as the maximum peak value of the response curve evaluated against the expected system response. Maximum overshoot is usually stated as a percentage of the steady-state value, which is referred to as percentage maximum overshoot. The percentage maximum overshoots for the FLC and P&O MPPT techniques are respectively 0.33 % and 1.1 %. As shown in Fig. 5 (b), by using P&O and INC methods, high and low-frequency fluctuations appeared on the delivered powers. While only low fluctuations can be observed with the proposed control method.

5.2. TEMPERATURE VARIATION

In this test, the temperature is varied, which is the most important environmental parameter that mainly affects the generated power by the PV system. The proposed control strategy is evaluated in terms of MPPs tracking and power quality compared to other control techniques at different temperatures (80 °C, 60 °C, 40 °C and 20 °C).

As shown in Fig. 6 (a), during temperature changes, the powers generated by the EPS using the three MPPT control methods successfully followed their MPPs. According to this figure, at the temperature of 80 °C, by the use of FLC, P&O and INC MPPT techniques, the values of PV power generated are 2.265 W, 2.258 W and 2.262 W, respectively. At the same temperature level (80 °C), the settling times for FLC, P&O and INC MPPT techniques are 66.6 ms, 61.86 ms and 94.36 ms, respectively. When compared to existing MPPT techniques, the suggested FLC method provides a somewhat higher amount of power. INC technique, on the other hand, has a longer settling time than the other MPPT approaches. When compared to the intended system response, maximum undershoot is defined as the response curve's minimal peak value. Maximum undershoot is commonly expressed as a percentage of the steady-state value, known as percentage maximum undershoot. P&O MPPT approache has 0.76 % maximum undershoots. Furthermore, as shown in Fig. 6 (b), the suggested FLC-based method provides a lower power ripple than the P&O and INC methods.

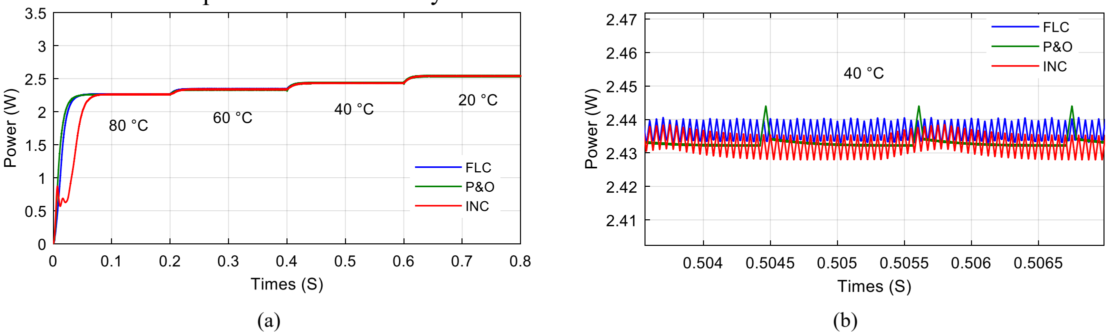


Fig. 6 – Output Powers obtained by different MPPT algorithms: (a) at different levels of temperature; (b) Zoom at 40 °C.

5.3. REAL ORBITAL CONDITIONS

During the orbital movement of a Nano-Satellite, the photovoltaic panels are very often not oriented toward the sun causing a rapid change in the irradiance and the temperature, which affects the position of their MPPs. In this test, to bring the study closer to the real orbital conditions, as illustrated in Fig. 7, the irradiance and the temperature around the Nano-Satellite are changing at the same time.

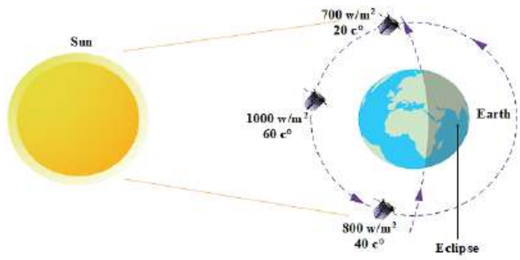
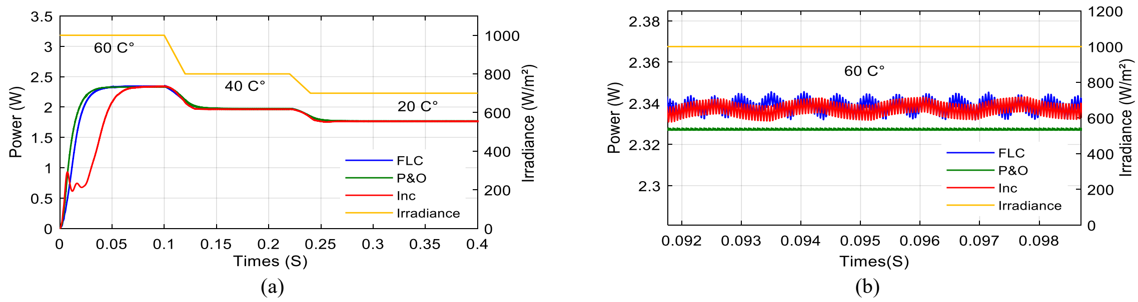
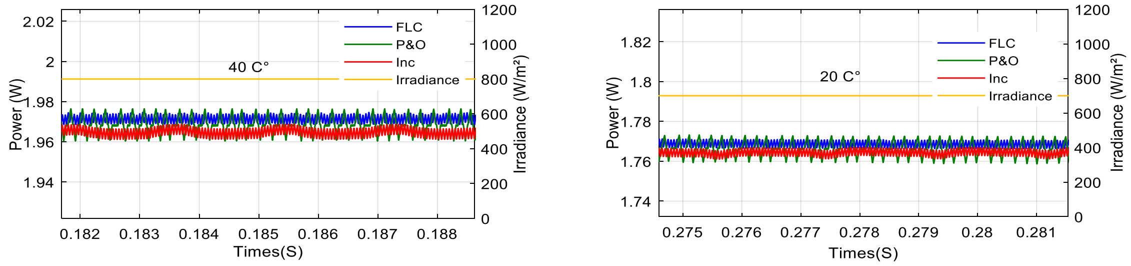


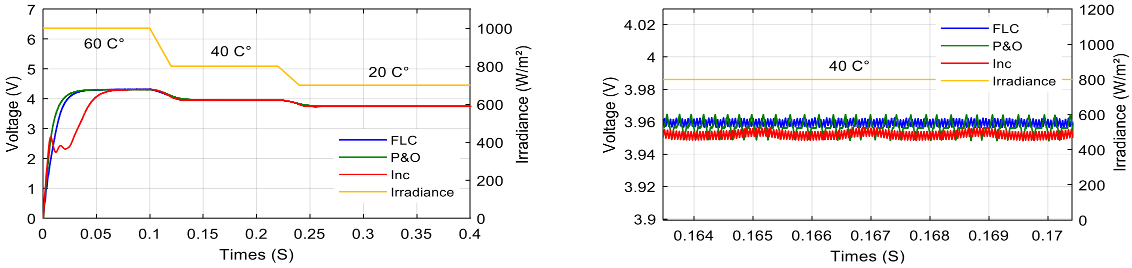
Fig. 7. Illustration of the Nano-Satellite in-orbit.





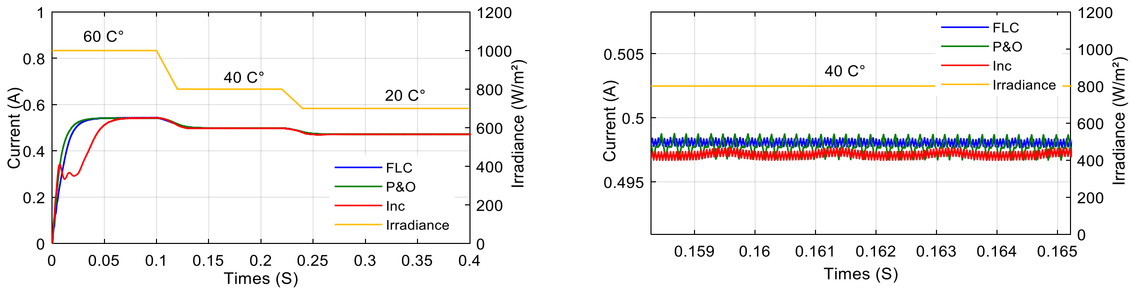
(c) (d)

Fig. 8 – Output Powers obtained by different MPPT algorithms: (a) at different levels of irradiance and temperature; (b) Zoom at 1000 W/m², 60°C; (c) Zoom at 800 W/m², 40°C and (d) Zoom at 700 W/m², 20°C.



(a) (b)

Fig. 9 – Output voltages obtained by different MPPT algorithms: (a) at different levels of irradiance and temperature; (b) Zoom at 800 W/m² and 40 C.



(a) (b)

Fig. 10 – Output currents obtained by different MPPT algorithms: (a) at different levels of irradiance and temperature; (b) Zoom at 800 W/m² and 40 C.

The generated powers from the three MPPT control methods efficiently tracked their MPPs throughout irradiance and temperature variations, as shown in Fig. 8. The values of PV power generated by FLC, P&O, and INC MPPT methods are 2.339 W, 2.327 W, and 2.337 W, respectively, at 1000 W/m^2 and 60°C. The settling times for FLC, P&O, and INC MPPT techniques are 67.6 ms, 61.92 ms, and 90.76 ms, respectively, at the same irradiance and temperature (1000 W/m^2 and 60 °C). The proposed FLC method provides a slightly higher amount of power with less oscillation compared to other MPPT techniques.

From Fig. 9 and Fig. 10, it is remarkable that the time response of the voltage and the current obtained from the INC method is slower than that obtained from the other MPPT control methods. Furthermore, as shown from these figures, by using P&O and INC methods, high and low-frequency fluctuations appeared on the delivered current and voltage. While only low fluctuations can be observed with the proposed control method.

The reported results indicate that the generated powers using the proposed method are more effective. P&O and INC delivered low performances with important oscillations and power losses. This is due in part to its sensitivity to the measurement's noises and variation of the intrinsic parameters of the system, unlike the proposed fuzzy method.

5.4. EFFICIENCY

For a more detailed analysis, a brief comparative study between the proposed FLC and other techniques, in terms of efficiency, average power *P,* and power variation *ΔP* is reported in Table 1.

Table 1

Efficiency of different MPPT algorithms

	1000 W/m² at 35 C°		
	P average	Δ*P* (oscillations)	Efficiency
FL	2,461	0,007	96 %
P&O	2,456	0,024	95,8 %
INC	2,452	0,011	95,6 %
The MPPT efficiency is calculated by the following relation: *Efficiency* = power from MPP technique / Ideal Power			

From this comparison, the proposed MPPT controller based on the FL technique shows the superiority in extracting larger and more stable average power with high efficiency. In addition, the oscillations obtained by FLC are three times less than compared to the P&O technique and almost half as much as the INC method.

6. CONCLUSION

In this paper, an overview of the maximum power point tracking (MPPT) control methods for the electrical power system (EPS) of nano-satellites is presented, in order to study the most efficient existing techniques to automatically adjust the duty cycle. Then, the proposed fuzzy logic control (FLC) based MPPT algorithms are presented and implemented to intelligently reaches the desired maximum power point (MPP). the contribution of this paper suggested the implementation of the duty cycle and the power variations of the PV system as inputs for the FLC. The consideration of such input variables allows the FLC algorithm to converge smoothly and rapidly to the exact MPP. The simulation results based on MATLAB/Simulink confirm that the proposed technique can provide more robustness and better performance for the optimal point tracking in terms of power oscillations, convergence speed, and accuracy resulting from any irradiance and temperature variations. These advantages lead to achieving a considerable and effective amount of stable energy gain over the life cycle of the EPS components.

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APPENDIX

The parameters of the triple-junction solar cell used in this paper are presented in Table 2:

Table 2

Parameters of the solar cell.

Electrical characteristics	Values at: pectrum AM0 WRC = 1367 W/m², T=28°C
V oc	2.667 V
I sc	0.506 A
R	0.546 Ω
Ki	0.32 mA/°C
I mpp	0.487 A
V mpp	2,371 V

The system parameters of the boost converter are presented in Table 3:

Table 3

Boost converter parameters.

Parameters	Values
Inductance L	0.00099H
Input Capacitor	0.7 e-4 F
Output Capacitor	2 e-3 F
Load resistor	7.95 Ohms

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