# A Comparative Analysis of MPPT Techniques for Grid Connected PVs

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**Abstract- Maximum Power Point Tracking (MPPT) is essential for the application of a photovoltaic (PV) energy system in order to extract the maximum possible power under variable conditions of irradiation and temperature. This paper deals with the implementation of different MPPT algorithms for a PV array installed for a system connected to the Grid: Perturb and Observe (P&O), Fuzzy Logic Control (FLC), Cuckoo Search (CS), and Beta algorithms were simulated in Matlab/Simulink and the results were analyzed and compared. Beta algorithm proved to have greater tracking power, minor power loss, great tracking speed, less time, and less oscillation than the other techniques.**

***Keywords-beta algorithm; cuckoo search; fuzzy logic controller; grid; photovoltaic; MPPT; P&O; THD***

## I. INTRODUCTION

Global increasing energy consumption and inevitable reduction of fossil fuel resources has pushed scientists to find and develop novel renewable energy resources [1, 2]. Solar energy is the most abundant renewable energy source [3, 4]. Photovoltaic (PV) energy becomes an important alternative as it is ubiquitous, environment friendly, freely available, it has low operational and maintenance costs, and less balance of systems [5]. Therefore, the technological innovations with the lower cost of PV modules lead to the implementation of PV grid-connected systems, especially small ones with Low Voltage (LV), which have gradually emerged [6]. However, the efficiency of a PV system is low, the output characteristics of solar arrays are nonlinear, and they vary with solar irradiance and temperature [7]. In order to make the PV system fully exploited, it must operate at its Maximum Power Point (MPP).

There are two categories of Maximum Power Point Tracking (MPPT) techniques: conventional MPPT algorithms which are simple and low-cost, yet they have poor efficiency. The second category consists of the MPPT methods based on intelligent control. These methods are complex with high efficiency [8]. Many research studies on the MPPT techniques have been reported. Authors in [9] fixed the duty cycle, in the simplest of methods that does not require any feedback, in which the load impedance is adjusted only once for the MPP and it is not adjusted again. Authors in [10], proposed an Adaptive Reference Voltage (ARV)-based MPPT technique to improve the performance of the constant voltage tracking technique by making it adaptable to weather conditions. Constant voltage control can be easily implemented with analog hardware. However, its MPPT tracking efficiency is low relative to those of other algorithms [9]. Authors in [11] used the SimPowerSystems platform in Matlab to design a PV system and a new GMPPT algorithm based on the open circuit voltage. The open circuit voltage method was adapted to a system under shading condition in [12]. This method has high tracking accuracy but does not always track the real peak and instead it causes the system to operate at a point close to the MPP. Authors in [13] proposed a hybrid MPPT method combined with the conventional Short Current Pulse (SCP) MPPT method and Perturb & Observe (P&O) method [14-15]. This algorithm is the most commonly used because of its ease of implementation for standalone PV systems. However, P&O has limitations that reduce its MPPT efficiency [16] while it requires complex control circuits [17].

Conventional MPPT methods are used satisfactorily, but they have the problem of low speed of convergence and high oscillations around the MPP. Since the P-V characteristic of a

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PV module is not linear, the conventional MPPT control method is not adequate. To resolve this problem, alternative MPPT control methods based on intelligent algorithms have been widely proposed and successfully applied .The most known intelligent methods for MPPT are Fuzzy Logic Control (FLC), Artificial Neural Networks (ANNs), and meta-heuristic algorithms [18]. Authors in [19] proposed ANNs as a global theoretical approach for predicting and tracking the MPP of solar panels. ANNs have been extensively used to model the complicated relationship between the inputs and outputs of nonlinear systems [19]. Several microcontrollers use FLC for MPPT. The FLC is preferred when the mathematical model of the control plant is difficult to obtain. This technique has been proposed in several research works to achieve the MPP. Authors in [20] mentioned that FLC can track the MPP quickly while it has better dynamic and steady-state performance. However, the main disadvantages of FLC are that the variation of irradiance can cause drift and the implementation is complex. The Particle Swarm Optimization (PSO) -based MPPT approach has been presented in [21, 22]. In [7], a modified version of PSO is developed. The PSO is highly potential due to its simple structure, easy implementation, and fast computation capability [23].

The main contribution of this paper is to determine the most efficient method to track the MPP of a grid connected PV system. The proposed methods are the Cuckoo Search (CS) algorithm [24-27], the Beta algorithm [28], P&O method, and FLC.

## II. MODEL DESCRIPTION OF THE PV MODULE

A simple equivalent circuit model for a PV cell is shown in Figure 1 [29]. The ideal case is presented by a current source in parallel with a diode, the real case of a PV cell is represented by the insertion of the resistances $R_s$ and $R_{sh}$ [30-31].

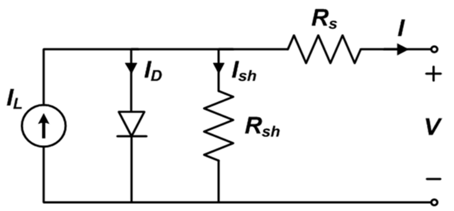



Fig. 1. Electric model equivalent of a PV cell.

The current of the PV panel is given by [32-33]:

$$I = I_L - I\left[\exp.\left(\frac{q.(V+R_S I)}{k.T}\right) - 1\right] - \left(\frac{V+R_S I}{R_{sh}}\right) \quad (1)$$

The current through the diode is given by:

$$I_D = I\left[\exp.\left(\frac{q.(V+R_{Sh}I)}{K.T}\right) - 1\right] \quad (2)$$

The solar cell output current is :

$$I = I_L - I_D - I_{Sh} \quad (3)$$

where I is the solar cell current (A), $I_L$ is the light generated current (A), $I_D$ is the diode saturation current (A), $R_S$ is the solar cell series resistance (Ω), q is the electron charge (1.6× $10^{-19}$C), K is the Boltzman's constant, T represents the cell temperature (K), V is the solar cell's output voltage (V), and $R_{Sh}$ is the solar cell's shunt resistance (Ω).

In this paper, the solar panel SPR-305E-WHT-D is considered. The specifications of this solar panel at steady state conditions (STC) of 25°C and 1000W/m$^2$ are the parameters used in simulations and are shown in Table I [34].

TABLE I. PARAMETERS OF THE CONSIDERED PV PANEL [34]

| Information | Value |
|---|---|
| Open circuit voltage | 64.2V |
| Short circuit current | 5.96A |
| Voltage at MPP | 54.7V |
| Current at MPP | 5.58A |
| Maximum power | 305.226W |
| Parallel strings | 66 |
| Series-connected modules per string | 55 |

## III. MPPT TECHNIQUES

### A. *Perturbation and Observation (P&O)*

The P&O method is one of the best MPPT approaches used to track the MPP in PV panels, combining easy implementation and simplicity of execution [35]. In P&O technique, we introduce a minor -predefined change to perturb the system and consequently cause the power variation of the PV module [30]. The PV output power is measured periodically and is compared with the previous power value [36-37]. If the power output increases, the same process continues, otherwise, the perturbation direction is reversed [36].

### B. *Cuckoo Search (CS)*

The CS algorithm [38] was proposed as an efficient metaheuristic optimization mechanism. This algorithm emulates the behavior of cuckoo birds in their reproduction process [24-25]. The cuckoo bird lays its eggs inside the nests of other birds instead of building its own [24]. It will choose the best nest for her eggs to hatch safely and breed a new generation of cuckoos. In some cases, in order to increase the chance of hatching, the cuckoo bird will make some effort as it lays its eggs strategically in a good position and sometimes drops the eggs of the host birds outside the nest. Some cuckoo species even produce eggs similar to the eggs of other bird species [25]. Upon hatching, the young cuckoos sometimes destroy the eggs of the host birds to increase the chance of getting more food. In some cases, host birds discover and destroy cuckoo eggs and may abandon their nests [27]. The CS optimization algorithm was developed, to track the MPPT of the solar PV. In order to make this algorithm suitable, some simplifications of the actual behavior are needed [39]. This algorithm works based on three rules [40]

- Each cuckoo bird will only lay one egg in a random host nest.
- Only the best nest, containing high quality organisms, will transmit the next generation of cuckoo birds.
- Finally, host networks are considered to have a fixed value. Levy flights are used to create new eggs and a step size of the cuckoo is determined with the Levy function as follows:

$$\text{Levy}(\beta) = L^{-\beta} \quad , 1 < \beta \leq 3 \quad (4)$$

where L is the flight length. The optimizing flight size coefficient α is regarded as a fraction of excreted eggs ($P_a$), where $P_a \in [0, 1]$.

### C. Fuzzy Logic Controller (FLC)

The main task of the FLC is to reach the MPP. However, the performance of the controller depends principally on human expertise. Fuzzy logic can work with imprecise inputs, it does not need the precise mathematical model of the system [41]. E(t) and $dE(t)$ are the FLC inputs given by (5) and (6) [42]:

$$E(t) = \frac{P_{PV}(t) - P_{PV}(t-1)}{V_{PV}(t) - V_{PV}(t-1)} = \frac{\Delta P}{\Delta V} \quad (5)$$

$$dE(t) = E(t) - E(t-1) = \Delta E \quad (6)$$

where $P_{PV}(t)$ and $V_{PV}(t)$ are the output power and the voltage of the PV module.

The FLC output is dD, which is the variable step size of the duty cycle:

$$dD = D(t) - D(t-1) \quad (7)$$

In this work, the triangular membership function is chosen for the inputs, due to its simplicity [43]. The proposed control model simulated in Matlab/Simulink is shown in Figure 2.

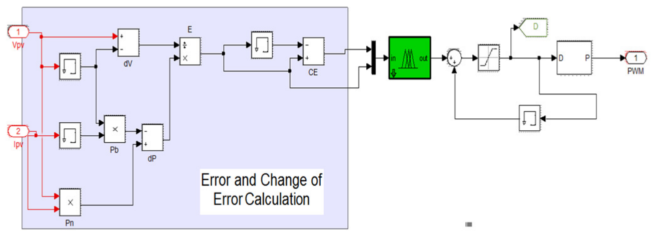



Fig. 2. Simulink model of the fuzzy logic controller.

### D. Beta Method

The Beta method has been detailed in [44]. In this method, an intermediate variable β is used to track the MPP [45]. The intermediate variable β is given as [29, 46]:

$$\beta = \ln\left(\frac{i_{pv}}{v_{pv}}\right) - c \times v_{pv} \quad (8)$$

$$c = q/(NsAKT) \quad (9)$$

where $i_{pv}$ and $v_{pv}$ are the PV current and voltage, c is the diode constant, q is the electron charge, A is the diode ideality factor, K the Boltzmann's constant, T is the temperature of the p-n junction, and Ns is the cell number of the PV module.

The Beta-based MPPT algorithm consists in tracking the reference β* that is calculated at the MPP [47]:

$$\beta^* = \ln\left(\frac{i_{pv_{mpp}}}{v_{pv_{mpp}}}\right) - c \times v_{pv_{mpp}} \quad (10)$$

where $v_{pv_{mpp}}$ and $i_{pv_{mpp}}$ are respectively the MPP voltage and current of the PV array at STC.

## IV. Simulation Results

This paper aims to test the feasibility and effectiveness of the considered MPPT methods to track the MPP of a grid-connected PV panel. The simulation of the overall system depicted in Figure 3 was carried out in Matlab/Simulink. The considered MPPT methods for this comparative study are: P&O, FLC, CS, and Beta. The PV array is modeled to have 66 strings and connected to the boost converter that operates with the MPPT controller. The linguistic variables in this study are defined as Positive Big (PB), Negative Big (NB), and Zero (ZE). Figure 4 presents the grid details connected with the PV.

In order to examine the effect of solar irradiation on module characteristic, the temperature of the cells was kept constant at 25°C. In Figures 5 and 6, the obtained I-V and P-V characteristics at different irradiation levels are shown.

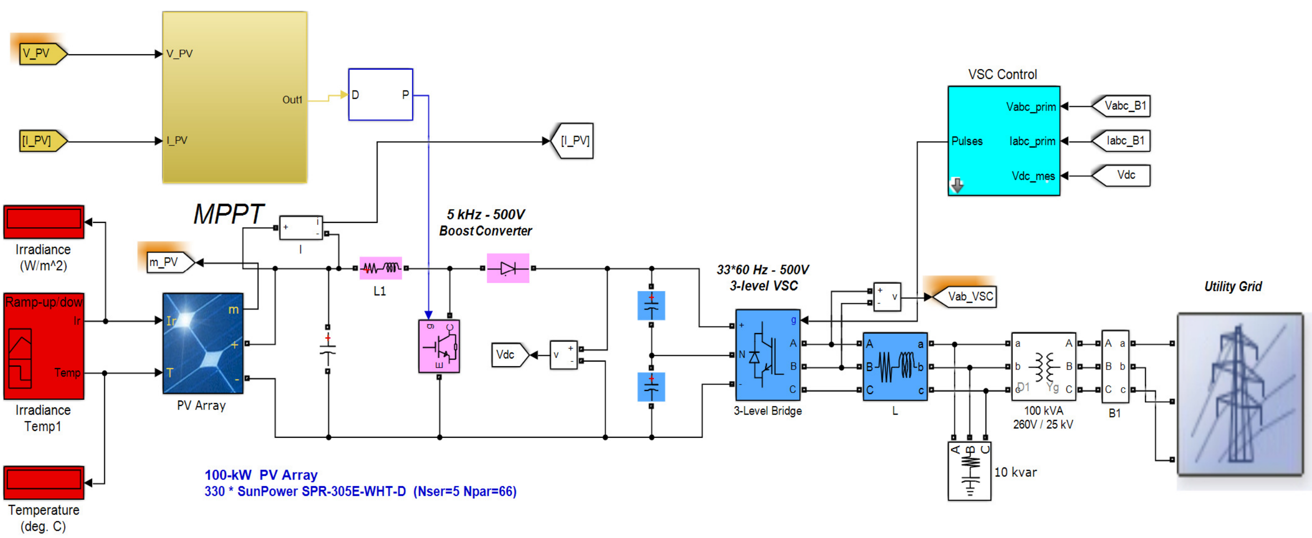



Fig. 3. 100 kW PV grid-connected PV array.

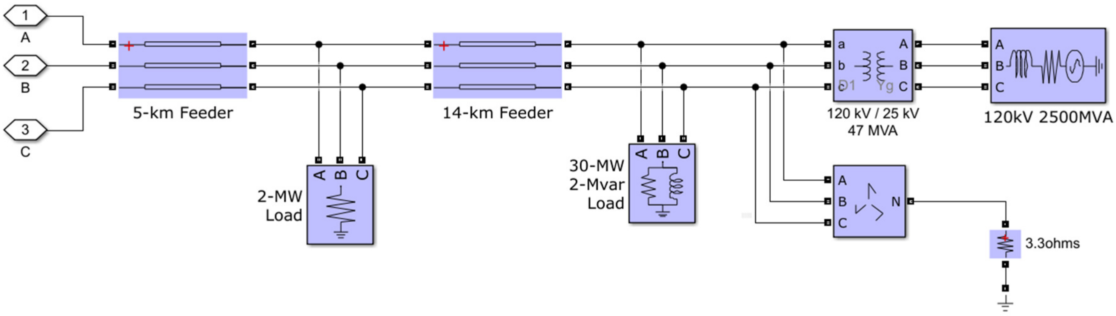



Fig. 4. Grid details.

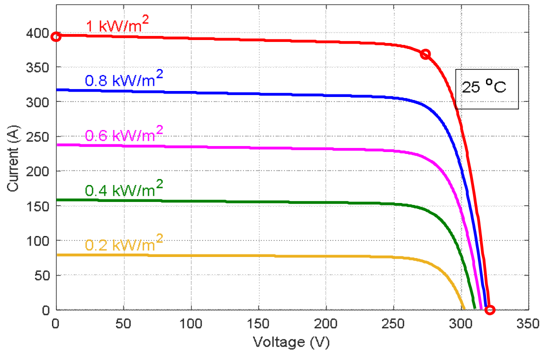



Fig. 5. I-V characteristic of the PV module at constant temperature and variable irradiation level.

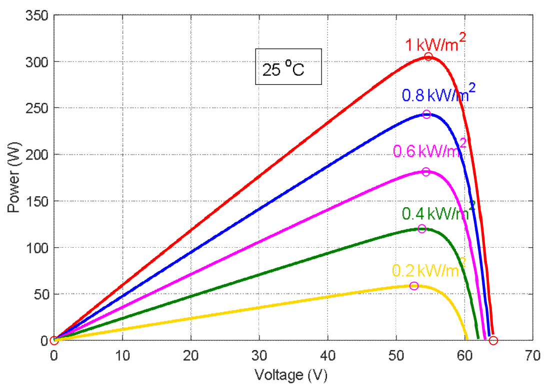



Fig. 6. P-V characteristic of the PV module at constant temperature and variable irradiation level.

A DC-DC boost converter is utilized as a power-conditioning unit between the PV module and the grid. The degree of the membership function of the inputs E, dE and the output dD is shown in Figure 7. The output voltage and current of the converter are converted by a three-phase inverter, to produce AC signals. This PV system is connected to the distribution line via a 100kVA transformer. To examine the robustness and the efficacy of the considered techniques in the tracking of MPP and re-tracking with changes in the weather conditions, the temperature of the cells is kept constant at 25°C and the irradiance level changes. Sun insulation of 1000W/m² is applied to the PV system in t ϵ [0, 1s]. Then, it is changed to 400W/m² between 1 and 1.5s. Finally it is stepped to 1000W/m² between 1.5 and 3s as shown in Figure 8.

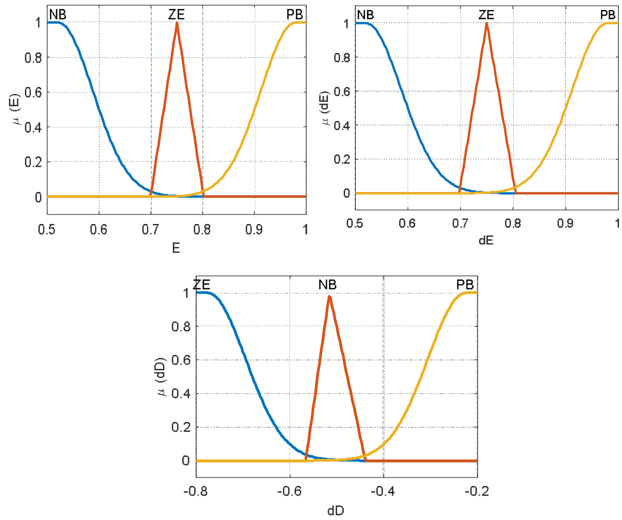



Fig. 7. Membership function inputs E, dE and output dD.

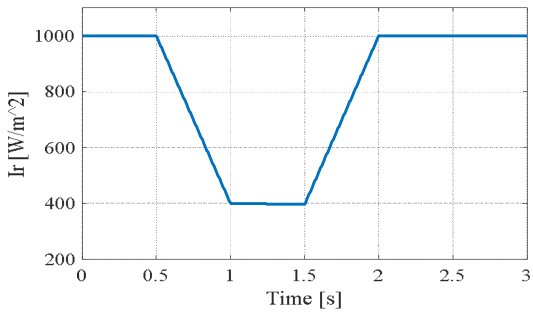
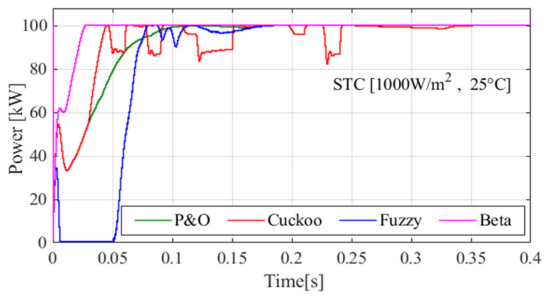



Fig. 8. Irradiation variation.

Figure 9 shows the output power of the considered methods. In Figure 9(a), we see the calculation of the Maximum Power Efficiency (MPE), that presents the main evaluation parameter of the MPPT in PV systems, in STC conditions. The MPE measures the percentage of the created power at certain time mentioned to the theoretical maximum created power at the same time. At STC, the MP (maximum power) is 100.7Kw. The power achieved by Beta, FLC, P&O, and CS was: 100.4, 100.3, 100.2, and 100.18KW respectively. The efficiency achieved by Beta, FLC, P&O, and CS was 99.7%, 99.6%, 99.5%, and 99.48% respectively. We see that Beta achieved higher efficiency than the other techniques .We can clearly note that in a transient state large oscillations can be observed in CS and FLC, which cause power loss.

(a)




(b)

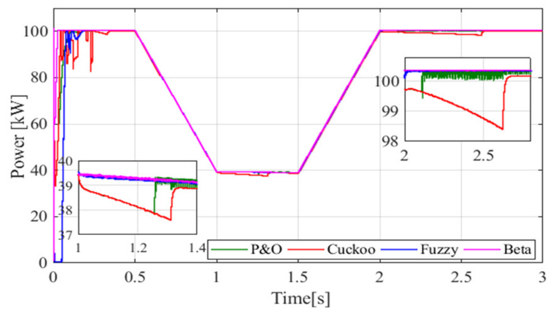



Fig. 9. PV system's power output: (a) STC, (b) sudden irradiance change.

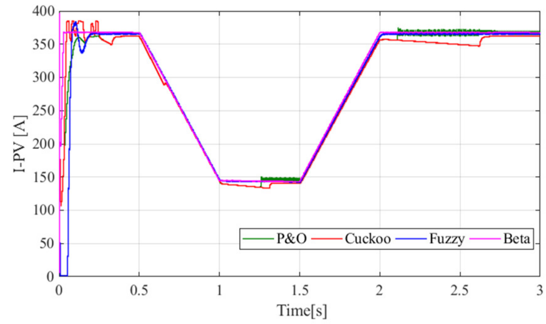
In order to extent the robustness of the MPPT techniques, settling time is an essential tool. The settling time in STC (Figure 9(a)) for Beta, FLC, CS, and P&O is 0.0256s, 0.1614s, 0.2411s, and 0.0914s respectively. So, Beta ensures the convergence to the MPP more rapidly.

In the zoomed part (1-1.4s) of Figure 9(b) the first step change is introduced at 1s. We stepped the irradiance from 1000W/m$^2$ to 400W/m$^2$. The FLC and Beta reach the MPP without an overshoot in short time, but the CS and P&O reach the MPP with large overshoot. In the interval from 2 to 3s, irradiance changed from 400W/m$^2$ to 1000W/m$^2$. With the CS algorithm, the oscillations around the MPP introduce a power with an average value equal to 98.3KW which creates a static error equal to 1.7kW. These results have confirmed the good performance and the high effectiveness of FLC and Beta. At t=2.6s, the CS reaches the MPP. CS takes a relatively long time to reach the MPP without an overshoot. P&O presents large oscillations around the MPP. The major inconvenience of P&O algorithm is its poor behavior following a sudden change in irradiance.

For the PV voltage ($V_{PV}$) and the PV current ($I_{PV}$) shown in Figure 10, we observe that in the transient state of PV voltage ($V_{PV}$), the CS and FLC algorithms present large oscillations between t=0 and t=0.2s. In the steady state, FLC, CS, and Beta are stable, but P&O in the intervals of the change of irradiance, presents large oscillations.

Figure 11 shows the DC output voltage regulation to connect the PV with the grid. In the zoomed part, with the quick change of irradiance at t = 1 s, Beta reached the reference voltage 500VDC quicker than the other algorithms.

(a)




(b)

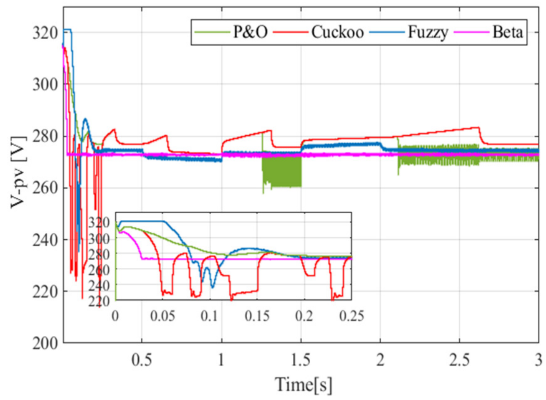



Fig. 10. (a) PV current, (b) PV voltage.

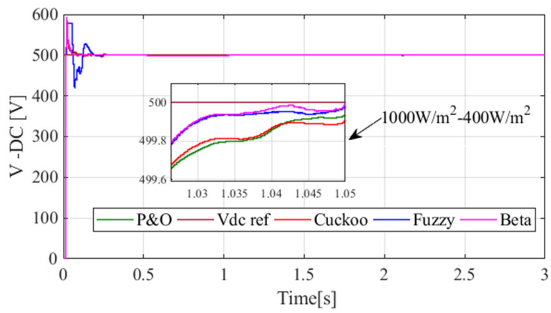



Fig. 11. The DC output voltage regulation at 500VDC.

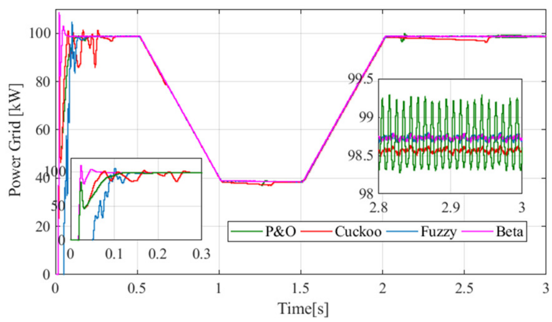



Fig. 12. Power injected into the grid.

Figure 12 shows the power injected into the grid. In the zoomed part (2.8-3s), P&O presents a large oscillation. The power achieved by Beta, FLC, P&O, and CS is 98.73, 98.72, 98.58, and 98.57kW respectively. This confirms the higher efficacy of the Beta algorithm.

(a)
(b)
(c)
(d)

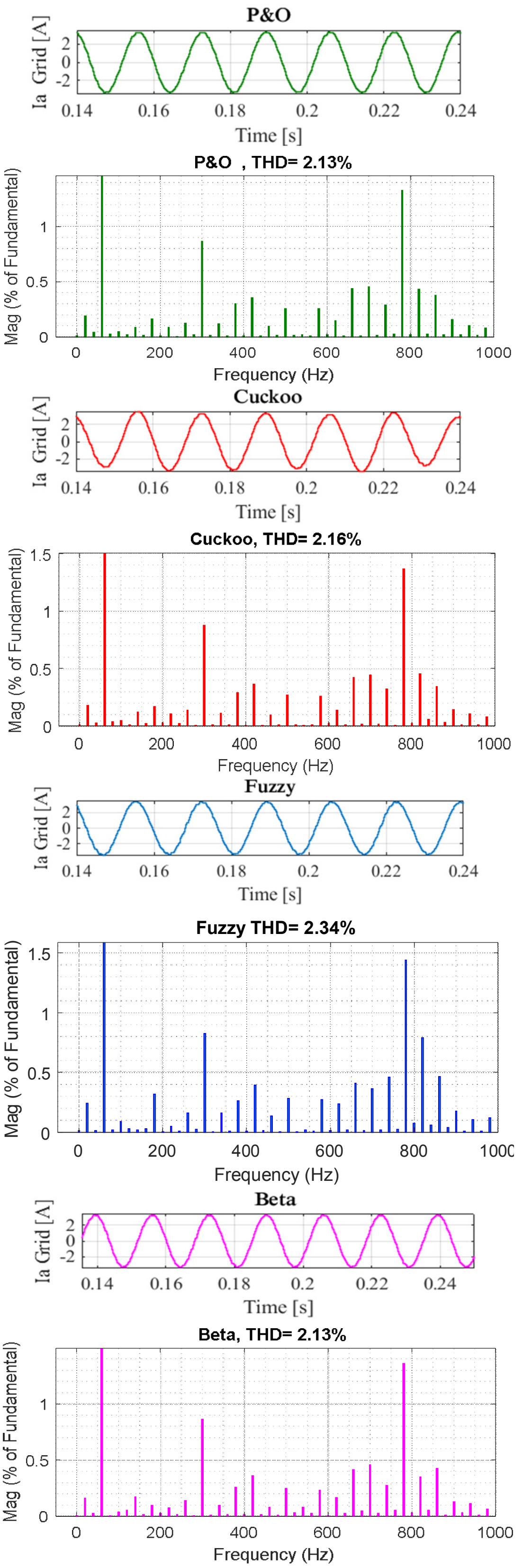



Fig. 13. AC output current waveform with grid connection, THD performance: (a) P&O, (b) CS, (c) FLC, (d) Beta.

The injected current to the grid has the shape of a sinusoidal wave, as shown in Figure 13 that confirms the effectiveness of the considered proposed controllers. To evaluate the quality of the injected current, the Fast Fourier Transform (FFT) analysis of the current is also shown in Figure 13. All the considered techniques show low THD , within the acceptable limit as per the standards IEC 61727, IEEE 1547 and IEEE 929 [48]. Beta and P&O perform better than the other algorithms with THD = 2.13%.

## V. Discussion

We note that the Beta method has satisfactory application in PV systems but with load resistance. In this paper our model is realized with a 100kW grid-connected PV system. The simulation results showed that the Beta method can address the two problems the existing MPPT methods face, namely the tradeoff between the steady-state oscillations and dynamic behavior and the tradeoff between high computational load and accuracy, since it shows a fast tracking speed in the transient stage, smaller oscillations in the steady-state and medium complexity of implementation. The performance of the Beta method as an MPPT technique is evaluated with respect to other known existing techniques, namely P&O [4], which introduces considerable oscillations near the MPP that lead to power losses, the FLC [6], and CS algorithm which presented large oscillations around the MPP contrarily to the results presented in [25].

To confirm the efficiency of proposed method, two comparisons were conducted:

- Power efficiency and settling time: The main evaluation parameters of the MPPT in PV systems are power efficiency and settling time. In this paper, the efficacy of the Beta technique was proved with efficiency of 99.7% and settling time of 0.0256s
- THD comparative study: Another criterion taken into account in evaluating the performance of the considered control algorithms is the rate of distortion of the network currents (THD). The results of the FFT analysis of the current were compared and validated.

## VI. Conclusion

The efficiency of a PV system is an essential indicator for assessing the power of grid-connected PV systems. MPPT performance is a key indicator. A MPPT algorithm must be used to track the operating point with the highest power output. In this esteem, this paper presented and compared four MPPT algorithms: P&O, FLC, CS, and Beta with regard to the achievement of the MPPT and the injection of sinusoidal current to the electric grid.

The simulation results showed the superior performance of the Beta algorithm in effectively and efficiently following the MPP with minimum oscillations and highest speed, even during a quick change in the solar irradiance.

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