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A comparative study of maximum power point tracking techniques for a photovoltaic grid-connected system

Purpose. *In recent years, the photovoltaic systems (PV) become popular due to several advantages among the renewable energy. Tracking maximum power point in PV systems is an important task and represents a challenging issue to increase their efficiency. Many different maximum power point tracking (MPPT) control methods have been proposed to adjust the peak power output and improve the generating efficiency of the PV system connected to the grid.* ***Methods.*** *This paper presents a Beta technique based MPPT controller to effectively track maximum power under all weather conditions. The effectiveness of this algorithm based MPPT is supplemented by a comparative study with incremental conductance (INC), particle swarm optimization (PSO), and fuzzy logic control (FLC).* ***Results*** *Faster MPPT, lower computational burden, and higher efficiency are the key contributions of the Beta based MPPT technique than the other three techniques.* References 51, table 3, figures 10.

Key words: **maximum power point tracking, incremental conductance, particle swarm optimization, fuzzy logic controller, Beta algorithm.**

Мета. *В останні роки фотоелектричні системи набули популярності завдяки низці переваг серед відновлюваних джерел енергії. Відстеження точки максимальної потужності у фотоелектричних системах є важливим завданням і складною проблемою для підвищення їх ефективності. Було запропоновано безліч різних методів керування відстеженням точки максимальної потужності (ВТМП) для регулювання пікової вихідної потужності та підвищення ефективності генерації фотоелектричної системи, підключеної до мережі.* ***Методи***. *У цій статті представлений контролер ВТМП, заснований на бета-методі, для ефективного відстеження максимальної потужності за будь-яких погодних умов. Ефективність ВТМП на основі цього алгоритму доповнюється порівняльним дослідженням з інкрементною провідністю, оптимізацією рою частинок та нечітким логічним управлінням.* ***Результати.*** *Швидше ВТМП, менші витрати на обчислення та більша ефективність є ключовими перевагами методу ВТМП на основі бета-методу порівняно з трьома іншими методами.* Бібл. 51, табл. 3, рис. 10.

Ключові слова: **відстеження точки максимальної потужності, інкрементна провідність, оптимізація рою частинок, нечіткий логічний контролер, бета-алгоритм.**

Introduction. Due to the advancement of industry and population growth the demand for energy is increasing, the exhaustion nature of fossil fuels and to reduce greenhouse emissions have drawn big interest to renewable energy which are sustainable, illimitable, and pollution-free [1, 2]. During the last decades, one of the solutions is solar photovoltaic (PV) energy drawing massive attention owing to its various advantages [3, 4]. PV cell transmutes photon energy into electrical energy whereas the PV cells are connected in series to construct PV module, moreover, PV module's series and parallel connection makes PV array [5].

One of the main hindrance of PV systems relates to the operation with the highest power under all environmental conditions such as changing irradiation and temperature, shading condition and ageing of module that require an effective algorithm named Maximum Power Point Tracking (MPPT) [6, 7] to increase efficiency and decrease the cost of PV system [8].

Several research papers suggest different techniques for achieving MPPT.

Perturb and observe (P&O), incremental conductance (INC) and hill-climbing (HC) are amongst the conventional MPPT algorithms have been widely adopted to track the MPP, once they are easy to implement and moderate cost [9, 10].

In addition, their tendency propensity gives rise to oscillations around MPP. These techniques suffer from the low tracking speed and high oscillations around MPP [11, 12].

In order, to settle this issue, various studies have been attempted by introducing optimization techniques such artificial intelligence methods, including fuzzy logic controller (FLC) [13, 14]. Fuzzy logic can deal with the nonlinearities because it does not require a mathematical model as well as a technical knowledge for the exact mode [15]. Artificial neural networks (ANN) methods are well adopted for handling nonlinearity in many applications [16, 17]. And machine learning (ML) [18] is used in exploring the most effective solution for MPPT. Their efficiency is highly dependent upon extensive training, which usually takes a long time and consumes much computation power for training the model [19, 20].

For more perfection and faster speed, recent studies have exhibited special interest on the bio-inspired MPPT algorithms, particularly swarm intelligence-based algorithms that have given better results than evolutionary algorithms MPPT controllers using particle swarm optimization (PSO) algorithms have been presented in [21, 22]. The difficult of this technique is the random initialization of the PSO particles that may cause premature convergence [23].

However, many hybrid methods, which include of more than two methods, have been proposed recent, the neural network has been trained by data that are optimized by genetic algorithms [6], neuro-fuzzy IC variable step size [24] and new hybrid fuzzy-neural is presented in [25], etc.

The goal of the paper. The current research work presents a design methodology of MPPT based on a Beta technique. The main advantage of Beta is fast tracking speed in the transient stage, small oscillations in the steady state and easy to implement. A comprehensive study has been presented for checking the effectiveness and robustness Beta technique with INC, FLC and PSO under rapid varying irradiance.

The proposed technique are validated a 100 kW on-grid PV array is modeled on MATLAB.

PV modeling. A PV module is generally is comprised of multiple cells in parallel and series to achieve the required output current and voltage whose purpose the connection series allows goes up the voltage, it is the same for the parallel connection increases the current [7, 26] which are further connected to make PV array of desired output. The equivalent circuit of the PV cell is shown in Fig. 1 [27, 28].

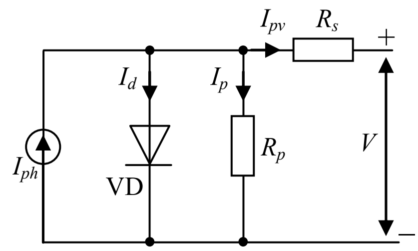


Fig. 1. The single-diode equivalent circuit of a solar cell

The output current generated here is presented in (1) – (3) [29, 30]:

$$I_{PV} = I_{ph} - I_d - I_p; \tag{1}$$

$$I_{PV} = I_{ph} - I_0\left[\exp.\left(\frac{(V + R_s I_{PV})}{a} - 1\right)\right] - \left(\frac{V + R_s I_{PV}}{R_p}\right), \tag{2}$$

$$a = \frac{N_s n k_B T}{q}, \tag{3}$$

where I_{ph} is the photo generated current; I_0 is the dark saturation current at standard test conditions (STC); R_s and R_p are the series and shunt resistance of the module respectively; a is the ideality factor; N_s is the series-connected PV cell(s); n is the diode ideality constant; k_B is the Boltzmann constant; T is the cell temperature (K); q is the electron charge.

MPPT techniques. Incremental conductance (INC) algorithm. The incremental conductance algorithm is based on the slope of the power-voltage ($\mathrm{d}P/\mathrm{d}V$) relation at the MPP is zero [31]. INC method is very precise in controlling the voltage even in rapidly changing atmospheric conditions [32, 33].

The equations implicated in the INC method are shown below:

$$P = (P_{PV} \times I_{PV}). \tag{4}$$

For MPP:

$$\frac{dP_{PV}}{dV_{PV}} = \frac{d(V_{PV}.I_{PV})}{dV_{PV}} = I_{PV}.\frac{dV_{PV}}{dV_{PV}} + V_{PV}.\frac{dI_{PV}}{dV_{PV}}; \tag{5}$$

$$\frac{dP_{PV}}{dV_{PV}} = I_{PV} + V_{PV}.\frac{dI_{PV}}{dV_{PV}}. \tag{6}$$

If:

$$I_{PV} + V_{PV}.\frac{dI_{PV}}{dI_{PV}} = 0 \rightarrow \frac{dI_{pv}}{dV_{pv}} = -\frac{I_{PV}}{V_{PV}} \text{ for MPP.} \tag{7}$$

If:

$$I_{PV} + V_{PV}\cdot\frac{\mathrm{d}I_{PV}}{\mathrm{d}I_{PV}} > 0 \rightarrow \frac{\mathrm{d}I_{PV}}{\mathrm{d}V_{PV}} > -\frac{I_{PV}}{V_{PV}} \text{ for } P<MPP. \tag{8}$$

If:

$$I_{PV} + V_{PV}\cdot\frac{\mathrm{d}I_{PV}}{\mathrm{d}I_{PV}} < 0 \rightarrow \frac{\mathrm{d}I_{PV}}{\mathrm{d}V_{PV}} < -\frac{I_{PV}}{V_{PV}} \text{ for } P>MPP. \tag{9}$$

In this method the MPP can be tracked by comparing the instantaneous conductance (I/V) to the INC ($\Delta I/\Delta V$) [34].

PSO algorithm. PSO technique is one of a swarm intelligence developed by Eberhart and Kennedy in 1995 [35, 36]. PSO is a global optimization algorithm for dealing with problems on a point or surface in an n-dimensional space which are linked with the best solution that has achieved by that particle [37]. Whereas the current state of the particle is, specify by the position x_i and the speed of movement v_i [38].

The particle has a random velocity vector. At each after iteration of the algorithm, the position is changed on the basis of new velocity, last best position and velocity, and distance from p_{best} and g_{best} [39].

The PSO algorithm is described by the following system of equations [40]:

$$v_i^{k+1} = wv_i^k + c_1 r_1 \left(p_{best_i} - x_i^k\right) + c_2 r_2 \left(g_{best} - x_i^k\right); \tag{10}$$

$$x_i(k+1) = x_i(k) + v_i(k+1), i \in \{1,...,N\}; \tag{11}$$

where x_i is the i particle position; v_i is the i particle speed; k is the number of repetitions; r_1, r_2 are the uniformly distributed random variables; w is the weighted inertia coefficient; c_1, c_2 are the cognitive and social coefficients, respectively; $p_{best\ i}$ is the best position used for the i particle; g_{best} is the best position of all particles.

The corresponding PV current and voltage to each sample of duty cycle are observed. The PV power which represents the fitness function of particle i is resolved. Afterwards, the new calculated power of particle i is compared with the power corresponding to $p_{best\ i}$ stored in the history. The new calculated power is choose the best fitness value of particle i. The velocity and position of each particle in the swarm must be modified by the above equations [41, 42]:

$$D_i^{k+1} = D_i^k + v_i^k; \tag{12}$$

$$v_i^{k+1} = v_i^k.w^k + c_1 r_1 \left(D_{best_i}^k - D_i^k\right) + c_2 r_2 \left(g_{best_i}^k - D_i^k\right). \tag{13}$$

When the maximum number of iterations is achieved, the algorithm will stop and give the optimum value of the duty cycle D_{best}.

The objective function is defined as:

$$P\left(D_i^k\right) > P\left(D_i^{k+1}\right), \tag{14}$$

where P is the output power; D is the duty cycle; k is the number of iterations; i is the number of current particles.

Fuzzy logic controller. FLC is the most famous control technique with a remarkable ability the nonlinearity applications. The advantages of this method are its simplicity and robustness and no need the precise mathematical model of a system [5, 27].

In FLC, the change of error (dE) and error (E) are the input variables at sampling time t. These are expressed by (15) and (16) [43, 44]:

$$E(t) = \frac{P_{PV}(t) - P_{PV}(t-1)}{V_{PV}(t) - V_{PV}(t-1)} = \frac{\Delta P}{\Delta V}; \tag{15}$$

$$dE = E(t) - E(t-1) = \Delta E, \tag{16}$$

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

The output variable of the controller is also to change in the duty cycle value (dD) [27]:

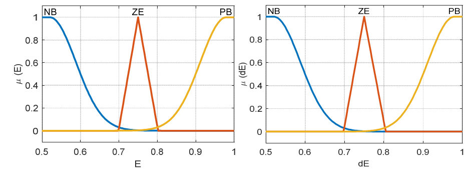
$$dD = D(t) - D(t-1). \tag{17}$$

The rule table of MPPT is shown in Table 1, and the membership functions are shown in Fig. 2.

Table 1

Rule base used in the fuzzy logic controller

E / dE	NB	ZE	PB
NB	PB	NB	ZE
ZE	NB	ZE	NB
PB	ZE	NB	PB



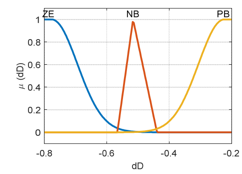


Fig. 2. Membership function for: (*a*) input E; (*b*) input dE; (*c*) output dD

The fuzzy inference is carried out by using Mamdani's method, and the defuzzification uses the centre of gravity to compute the output of this FLC which is the duty cycle.

Beta method. The beta parameter based MPPT algorithm was presented in [45], where the coefficient beta (β) is expressed by (18) to find an intermediary value amongst the voltage and current [46]:

$$\beta = \ln\left(\frac{I_{PV}}{V_{PV}}\right) - C \times V_{PV} , \qquad (18)$$

where V_{PV} and I_{PV} are the PV module output voltage and output current, respectively; C is the diode constant, obtained from (19) [47]:

$$C = q / N_s A k_B T , \qquad (19)$$

where q is an electronic charge; k_B is Boltzmann constant; A is diode quality factor; T is the ambient temperature (K); N_s is the cell number of the module.

Firstly, the voltage and current are measured, so the value of β can be continuously calculated. The value of β remains within a narrow band as the array operating point approaches the MPP.

The β is defined once based on PV characteristics at STC, using the MPP voltage and current, as expressed by (20):

$$\beta^* = \ln\left(\frac{I_{PV_{mpp}}}{V_{PV_{mpp}}}\right) - C \cdot V_{PV_{mpp}} , \qquad (20)$$

where I_{PVmpp}, V_{PVmpp} are the respective MPP current and voltage of the PV array at STC.

Simulation results and discussion. In this section, we will present the obtained results of the global system for the control of the grid-connected PV system. The simulations are performed using MATLAB. The suggested MPPT methods for this comparative study are: INC, FLC, PSO and Beta controllers. Figure 3 depicts the PV arrays of 100 kW connected to 25 kV grid using MATLAB software. A filter is used to reduce the harmonics before connecting the inverter a 260 V / 25 kV transformer [48]. The parameters of the SPR-305-WHT PV module used in the simulation are listed in Table 2.

The PV farm consists of 66 parallel strings each string consists of 5 series PV modules with each module rated at 305.2 W. The total power of the array is 100.7 kW at STC [49]. PV module characteristics; current-voltage characteristics, power-voltage characteristics are shown in Fig. 4.

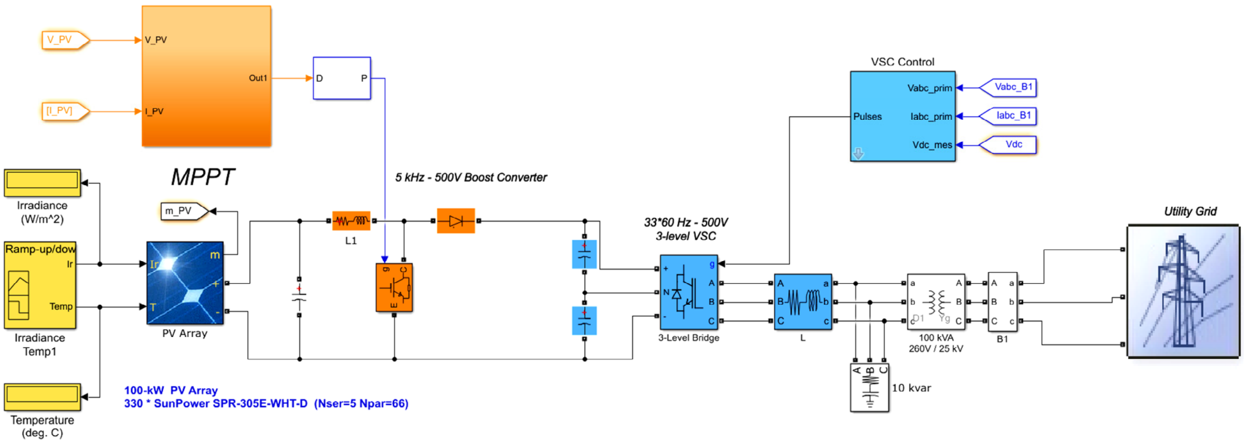


Fig. 3. Simulink model of the 100 kW grid-connected PV system

Table 2

PV module specifications [50]

Parameters	Value	Parameters	Value
Maximum power	305.02 W	V_{max} (voltage at the maximum power)	54.7 V
Peak efficiency	18.7 %	Short circuit current	5.96 A
Number of cells	96	Open circuit voltage	62.4 V
I_{max} (current at maximum power)	5.58 A	NOCT (Nominal operating cell temperature)	45°C

The proposed system is also validated by varying the irradiance level of the PV system with a constant temperature for calculating the performance evaluation. To investigate the solar irradiation change resulted from weather conditions variation, two consecutive step changes in solar irradiation are applied, which decrease from 1 kW/m^2 to 0.5 kW/m^2 at t = 0.5 s and increase to 1 kW/m^2 at t = 1.5 s, respectively (Fig. 5). While the temperature is assumed to be constant at 25 °C.

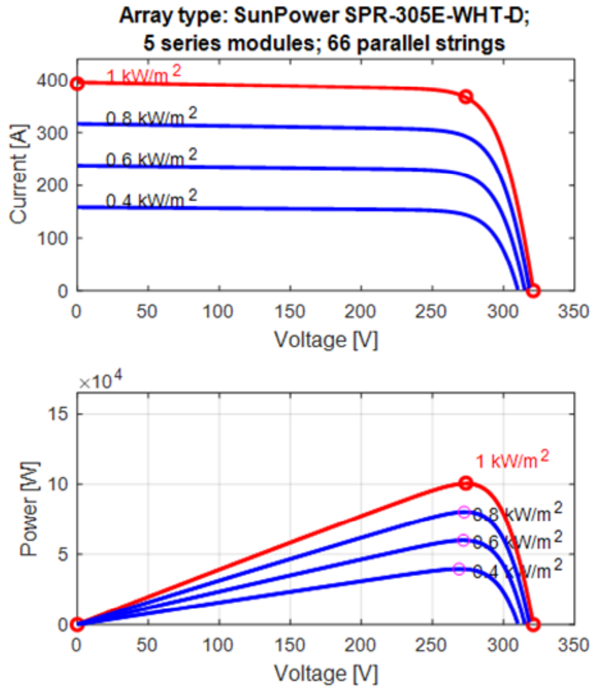


Fig. 4. *I-V* and *P-V* characteristics of the PV module at various irradiances and constant temperature

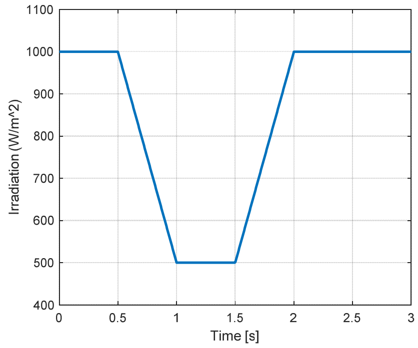


Fig. 5. The solar irradiance pattern applied to PV arrays

Figure 6 shows the output voltage variation of the PV system. The Beta technique has a good transition response 0.02802 s and a very fast system reaction against the set point change compared to another controller.

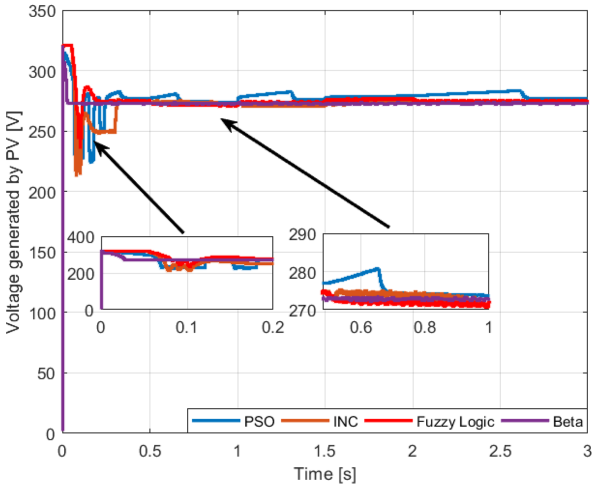


Fig. 6. PV voltage V_{PV}

Figure 7 illustrates the time evolution of photovoltaic current for different techniques. The system with INC controller suffers from failure in tracking of current. So we can see that Beta algorithm is better than other algorithm.

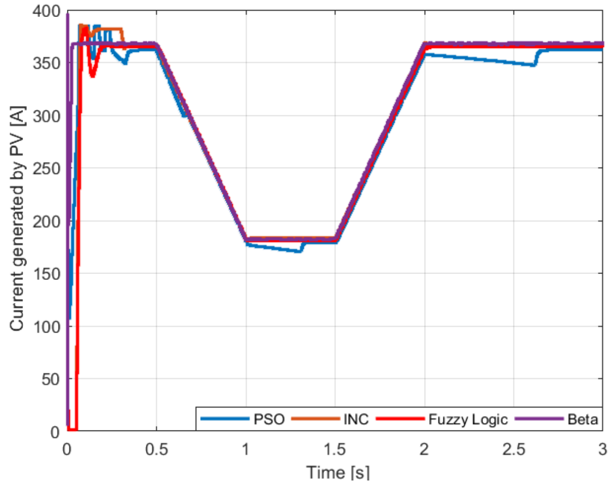
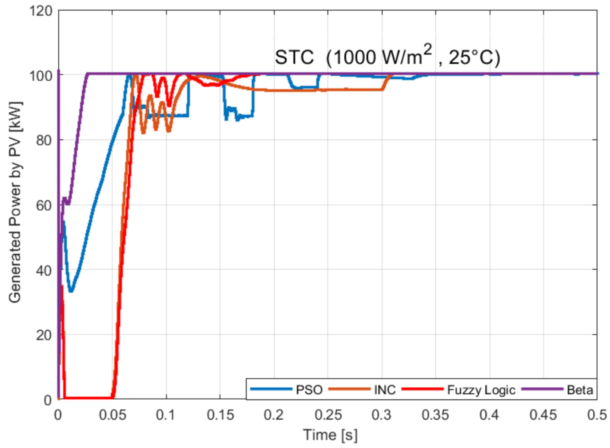
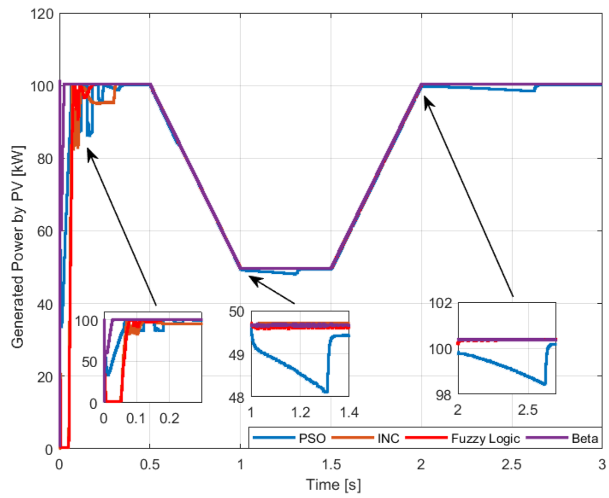


Fig. 7. PV current I_{PV}

Figures 8,*a* and 8,*b* indicate the PV system's power output: at STC condition and sudden change of irradiance.



a



b

Fig. 8. PV system's power output:
(*a*) at STC condition; (*b*) sudden change of irradiance

The first step. The proposed MPPT methods is first compared under constant conditions 1 kW/m^2 and 25 °C as shown in Fig. 8,*a*.

From the simulation results, the fuzzy logic based MPPT produce the output power of 100.37 kW, INC

100.37 kW, and PSO 100.18 kW whereas the Beta based MPPT method generates 100.4 kW output power during the 0–0.5 s this strategy demonstrated performance superiority. Efficiency can be determined as the total output power of the system to the total input power of the system. Formula can be written below it is [51]:

$$\eta = \frac{P_0}{P_{\max}} \cdot 100\% , \qquad (21)$$

where P_0 is the energy obtained from the PV module; $P_{\max}$ is the value of the maximum real power.

The output power of PV system at STC condition for different MPPT methods is compared in Fig. 8,*a*.

It is clear that the efficiency of tracking using PSO MPPT method is 99.48 % which is smaller than that obtained using other methods. In this situation, the Beta MPPT method tracks the maximum power successfully with efficiency of tracking 99.7 %.

Time to capture MPP for the Beta MPPT method is 0.0256 s, for PSO is 0.3349 s, for INC the time is 0.307 s and for the fuzzy logic method is 0.1614 s. This result shows that the speed of Beta MPPT method to capture MPP is best. It has the shortest MPP tracking period, the least transient fluctuations, zero oscillation around MPP and high tracking accuracy, this means the lowest power loss.

The second step. From Fig. 8,*b* in zoomed part [1 s – 1.4 s] where the irradiance level is changed from 1 to 0.5 kW/m^2. The Beta and fuzzy logic controller succeeds in instantaneously tracking the maximum power point, the oscillations are lesser at MPP in steady state in comparison the PSO and INC suffer from oscillations at MPP and tracking speed is less.

The third step. Another test is implemented to further validate the performance of the proposed controller. The application of irradiance from 0.5 to 1 kW/m^2 at t = [2 s – 3 s] (Fig. 8,*b*).

The results show that fuzzy and Beta are capable of tracking MPP under a sudden change in irradiance. Besides, the power loss in steady state due to MPP is quite low and power oscillations around MPP are minor with a higher convergence rate than others. INC and PSO method require a high response time and it has large power oscillations at MPP.

The equation representing power loss is given in (22). It can be represented in %:

$$\Delta P_{Loss} = \frac{P_{\max} - P_0}{P_{\max}} \cdot 100\% , \qquad (21)$$

From Table 3 it can also be observed that the dynamic response with high efficacy of Beta technique under variation irradiance of 0.5 kW/m^2 to 1 kW/m^2 at [2 s – 3 s] compared with the methods studied.

Table 3

Results comparison for the four MPPT

Algorithm	Power generated by PV, kW	Stelling time, s	ΔP_{loss}, %
PSO	100.18	0.69	0.51
INC	100.36	0.03	0.33
Fuzzy logic	100.37	0.023	0.32
Beta	100.40	0.02	0.29

The proposed method is efficient and extracts the maximum power with minimum error, it converges fast and precisely compared to other methods, it treats in a flexible and clear way and is very effective for this type of problem.

But this method needs only the knowledge of the I-V characteristics and which is much related to the specific conditions of PV system. The use of this method requires an in-depth understanding of physical behavior, mathematical modeling, and computer science.

It is very apparent, in dynamic climatic change conditions at time periods (1, 1.5 and 2 s) the INC, FLC and PSO controller suffer to track rapid or fast changing conditions, with an error and low tracking efficiency.

It can be said that despite the sudden changes in irradiance, the proposed method performs better in terms of stability and power extraction.

Figure 9 shows the reference signal for the voltage controller and the resulting DC link voltage. The voltage is constant throughout the time (500 V) and no boost converter output voltage values up and down when the radiation values increases and decrease respectively. So, the Beta technique has the fastest converge speed among all the other suggested MPPT techniques.

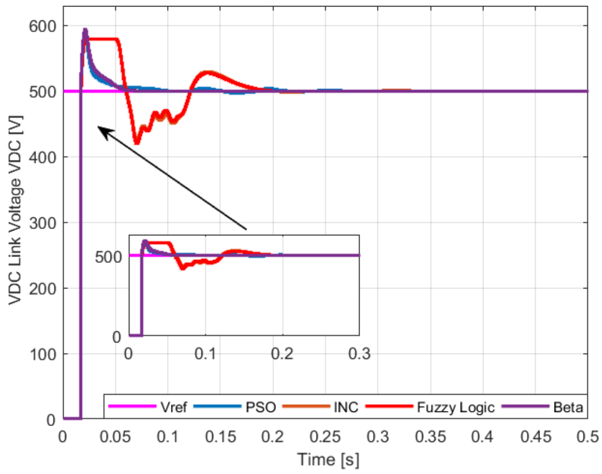


Fig. 9. Reference voltage and actual DC link voltage

Figure 10 shows the time evolution of the active power which flows between the analyzed system and the main grid. The power achieved by Fuzzy logic is 98.70 kW; Beta is 98.75 kW; PSO is 98.55 kW and INC is 98.65 kW. This confirms that Beta presented negligible power oscillations in steady state and the lowest convergence times.

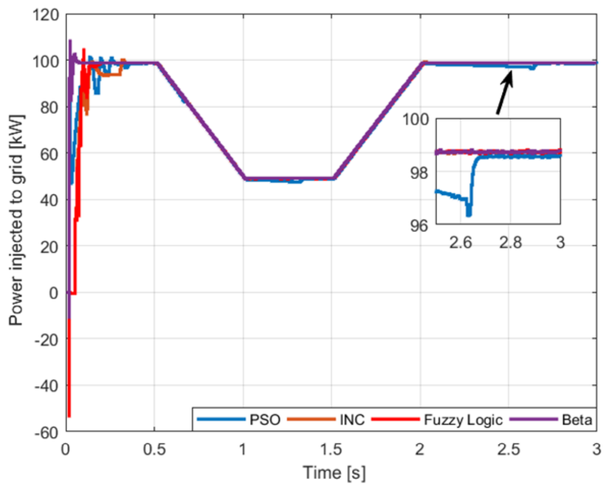


Fig. 10. Power injected to grid

From the simulation results, the Beta based MPPT algorithms is realized with a 100 kW PV array connected to a 25 kV grid whither in the literature application in PV systems with the load resistance. From the data, it has been demonstrated that the Beta controller has a better time response process. Since the computations show that the Beta achieves a high efficiency for all the irradiance ranges whereas the other methods fail in achieving high efficiency. It also, avoid power loss around the MPP. However, this technique depends on the PV characteristics.

Conclusions.

The use of photovoltaic systems to generate electricity is developing around the world. The photovoltaic system efficiency is a crucial index to estimate the performance of grid-connected photovoltaic systems where the maximum power point tracking performance is a key word to improve and increase the efficiency of this structure.

This paper presents the control of a grid-connected photovoltaic system using: incremental conductance, particle swarm optimization algorithm, fuzzy logic control and Beta for the achievement of photovoltaic maximum power point tracking.

The comparative study confirmed that the Beta controller was presented as an excellent solution regarding the low oscillations, the highest speed, and efficiently tracking the maximum power point even during an abrupt change in the solar irradiance.

Conflict of interest. The authors declare no conflict of interest.

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