A new PSO-PID variable step size MPPT controller for PV systems under fast changing atmospheric conditions

S. Messalti [1*], A. Harrag [2†] and A. Loukriz [1]

[1] Electrical Engineering Department, Faculty of Technology, Mohamed Boudiaf University
B.P. 166 Ichbilia, 28000 M'Sila, Algeria

[2] CCNS Laboratory, Electronics Department, Faculty of Technology
Ferhat Abbas University, Cite Maabouda, 19000 Setif, Algeria

(reçu le 15 Décembre 2017 - accepté le 28 Décembre 2017)

Abstract - *In this paper, a new modified variable step P&O maximum power point tracking algorithm using Proportional-Integral-Derivative controller tuned by particle swarm optimization is proposed. The classical fixed step P&O algorithm has good performances due to its simplicity and easy implementation; however, failing and inefficiency especially in case of rapidly changing atmospheric conditions, as well as oscillation around the maximum power point decreasing by the way the convergence speed are the main drawbacks. To solve these drawbacks, a new variable step P&O algorithm using Particle Swarm Optimization based Proportional-Integral-Derivative controller is presented. A theoretical analysis of the proposed algorithm has been provided using a boost converter connected to a Solarex MSX-60 model. Analysis and comparison between the classical fixed step P&O and that developed Particle Swarm Optimization variable step are presented. The efficiency and improvements of the proposed algorithm in transient, steady-state and dynamic responses, related to ripple, overshoot and response time, especially under rapidly changing atmospheric conditions have been demonstrated.*

Résumé - *Dans cet article, un nouvel algorithme MPPT modifié P&O à pas variable utilisant un contrôleur Proportionel-Integral-Dérivatif, 'PID' ajusté par optimisation à essaim particulaire est proposé. L'algorithme P&O classique à pas constant possède de bonnes performances en raison de sa simplicité et de son implémentation facile; cependant, il présente des dysfonctionnements et des inefficiences particulièrement dans les cas où les conditions atmosphériques changent rapidement, ainsi que lors des oscillations autour du point de puissance maximum par la voie de la vitesse de convergence. Pour résoudre ces inconvénients, un nouvel algorithme P&O à pas variable utilisant un contrôleur 'PID' basé sur une optimisation à essaim particulaire est présenté. Une analyse théorique de l'algorithme proposé a été réalisée en utilisant un convertisseur boost relié à un modèle Solarex MSX-60. Une analyse comparative entre la P&O classique à pas constant et celle à pas variable développé par optimisation à essaim particulaire est présentée. L'efficacité et les améliorations apportées par l'algorithme proposé en régime transitoire, permanent et les réponses dynamiques liées aux ondulations, dépassements, et temps de réponse, particulièrement dans des conditions atmosphériques qui changent rapidement ont été démontrées.*

Keywords: Photovoltaic Cell modeling - MPPT Algorithm - P&O Algorithm - PID Controller, Particle Swarm Optimization - Variable Step Size.

1. INTRODUCTION

The rapid development of modern life styles requires more and more efficient energy sources, which a large part of global energy production comes the conventional energy sources. However the use of these sources produces the greenhouse emissions

[*] messalti.sabir@yahoo.fr
[†] a.b.harrag@gmail.com

and therefore an increase in the warming and pollution. The additional dilemma is that excessive consumption of natural resources reduces the stock reserves of this type of energy in a hazardous manner for future generations and has raised concerns over the energy security. Hence the problem of energy is more and more aggravating.

For these reasons, many countries have reoriented their energy strategies to new forms of green energy called "renewable energy" that are currently too expensive and relatively inefficient. Renewable energy is the energy which comes from natural resources such as sunlight, wind, rain, tides, geothermal heat and various forms of biomass. These resources are renewable and can be naturally replenished continuously.

This energy cannot be exhausted and is constantly renewed. Among the renewable energy sources, photovoltaic (PV) energy is an attractive source of energy and it is one of the most important renewable energy sources that has been increasing worldwide year by year, it has been continuously growing at a rapid race over the recent years[1-5]. The photovoltaic (PV) system technologies are rapidly expanding and have increasing roles in electric power technology since it exhibits many merits such as cleanness, simple in design requiring very little maintenance and no noise, abundant and available almost everywhere unlike other types such as wind turbines, biomass, geothermal, waves, etc... [1-3].

Although the large number of aforementioned Photovoltaic advantages, it still presents some drawbacks comparing to conventional energy resources especially its low conversion efficiency which is only in the range of 9 - 17 %, high fabrication cost, and nonlinear characteristics. Therefore, the energy harvesting at maximum efficiency is not simple enough [1,3].

To overcome these problems, maximum power point tracking control algorithm is required to adjust continuously the power interfaces to obtain the maximum power available from a PV array at any given time under variable conditions (insolation, shading, temperature, load). There is a unique operating point on the array's power - voltage (P-V) curve called the maximum power point (MPP), where the power generation is maximum. MPPT controllers operates by sensing the current and voltage of the PV array; the power is calculated and accordingly the duty cycle of the converter is adjusted to match the maximum power point (MPP) [5-10].

In the last decade, enormous number of MPPT techniques have been proposed and improved continuously. These methods include perturbation and observation (P&O) algorithm [2, 9-11], Incremental Conductance (IC) method [12-14] and Hill Climbing (HC) [15-17], neural network, fuzzy logic, particle swarm optimization (PSO) based MPPT and genetic algorithms have been proposed [5, 18-19]. Fractional Open-Circuit Voltage (FOCV), Fractional Short-Circuit Current (FSCC) [20-22].

In addition, Many combined or hybrid methods have been developed such as genetic algorithm-neural networks (GA-ANN) [23], and genetic algorithm- fuzzy logic controller (GA-FLC) [24]. Among all the previous MPPT strategies, the P&O, IC and Hill climbing algorithms are widely employed due to easy implementation and high tracking accuracy.

However the performance depends essentially to the fixed step size, a faster dynamics with large oscillations around the MPP is obtained using a large step size, a slow tracking speed and less oscillations around the MPP is obtained using a small step size.

Hence, the trade off between the dynamics and steady state accuracy must be established by the corresponding design. To overcome this problem, variable step-size MPPT methods have been proposed [1, 5, 12, 14, 25].

In this paper, a new modified variable step P&O maximum power point tracking algorithm using Proportional-Integral-Derivative controller tuned by particle swarm optimization is proposed. The classical fixed step P&O algorithm has good performances due to its simplicity and easy implementation; however, failing and in efficiency especially in case of rapidly changing atmospheric conditions, as well as oscillation around the maximum power point decreasing by the way the convergence speed are the main drawbacks.

To solve these drawbacks, a new variable step P&O algorithm using Particle Swarm Optimization [26] based Proportional-Integral-Derivative controller is presented. A theoretical analysis of the proposed algorithm has been provided using a boost converter connected to a Solarex MSX-60 model.

Analysis and comparison between the classical fixed step P&O and that developed Particle Swarm Optimization variable step are presented. The efficiency and improvements of the proposed algorithm in transient, steady-state and dynamic responses, related to ripple, overshoot and response time, especially under rapidly changing atmospheric conditions have been demonstrated.

2. SYSTEM DESIGN AND CHARACTERISTICS

Photovoltaic systems are designed around the photovoltaic cell. Since a typical photovoltaic cell produces less than 3 watts at approximately 0.5 volt DC, cells must be connected in series-parallel configurations to produce enough power for high-power applications. Typically the cells are connected in series to form PV modules.

Modules are then connected in series to form strings in order to reach a voltage level that meets the input requirements of the power processing system. The desired power level of the PV plant is reached by connecting a number of strings in parallel leading to an increase of the current level of the PV field [27].

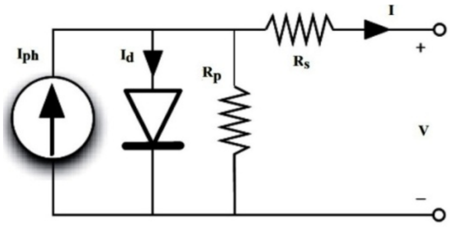

Fig. 1: Equivalent Single-diode model of solar cell [28]

I is the PV array output current, I_{ph}, is the cell photocurrent that is proportional to solar irradiation, I_d is the current through the diode, R_s and R_s are the series and parallel resistors of the cell, respectively.

Based on single-diode model presented in figure 1, the output current of the solar cell can be expressed as [29]:

$$I = N_p I_{ph} - N_p I_{rs} \left(e^{\left(\frac{q\,(v + R_s . I)}{A.k.T.N_s} \right)} - 1 \right) - N_p \left(\frac{q\,(v + R_s . I)}{N_s . R_p} \right) \qquad (1)$$

where, I_{rs} is the cell reverse saturation current respectively; k is the Boltzmann’s constant (1.3806503×10^{-23} J/K); q is the electron charge (1.60217646×10^{-19} °C); T is the temperature in K; V is the cell output voltage; A is the diode ideality constant; N_s is the number of PV cells connected in series; N_p is the number of PV cells connected parallel.

The generated photocurrent I_{ph} is related to the solar irradiation by the following equation:

$$I_{ph} = \left[I_{sc} + k_1 (T - T_r)\right] . S/1000 \quad (2)$$

where, I_{sc} is the cell short-circuit current at reference temperature; k_i is the short-circuit current temperature coefficient; T_r is the cell reference temperature; S is the solar irradiation in W/m^2.

The cell's saturation current is varies with temperature according to the following equation:

$$I_{rs} = I_{rr} \left[\frac{T}{T_r} \right]^3 \exp\left(\frac{q.E_G}{k.A} \left[\frac{1}{T_r} - \frac{1}{T} \right] \right) \quad (3)$$

where, I_{rr} is the reverse saturation at T_r; E_G is the band-gap energy of the semi conductor used in the cell.

The electrical characteristics of a PV panel working in uniform conditions are plotted in figures 2 to 5 in normalized units. T_{max} and S_{max} can be assumed as the values used for testing the panel in standard conditions. The characteristics depend on the type of cells, materials, and technical solutions adopted for manufacturing the panel.

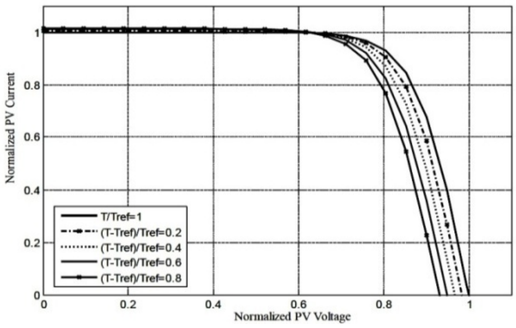

Fig 2: Current vs. voltage characteristic of a PV panel: effect of temperature T

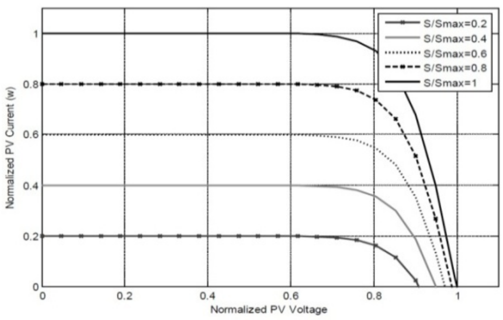

Fig 3: Current vs. voltage characteristic of a PV panel: effect of irradiation S

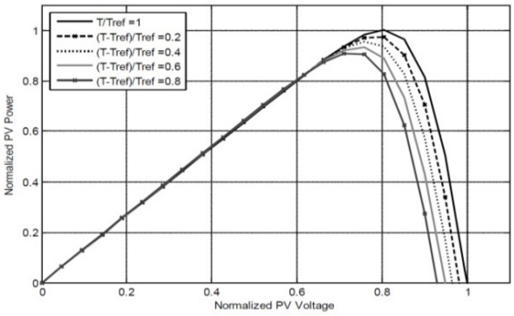

Fig 4: Power vs. voltage characteristic of a PV panel: effect of temperature T

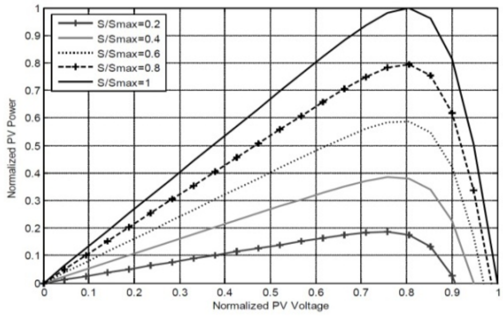

Fig. 5: Power vs. voltage characteristic of a PV panel: effect of irradiation S

The characteristics put into evidence the presence of a maximum power point (MPP) and show that the curves exhibit three particular points:

• The short-circuit (SC) condition, characterized by a zero voltage at the PV module terminals and by a short-circuit current I_{sc},

• The open-circuit (OC) condition, characterized by a zero current in the PV panel terminals and by an open-circuit voltage V_{oc},

• The MPP, at which the current value is I_{MPP}, the voltage value is V_{MPP}, and the power $P_{MPP} = V_{MPP} \times I_{MPP}$ is the maximum the PV panel is able to deliver in the temporary operating conditions.

From figures 2 to 5, we can see the strong dependence of the panel performances on the temperature and the irradiance level. The temperature has a significant effect on the open-circuit voltage value. On the contrary, the temperature has a negligible effect on the short-circuit current value.

While the irradiance variation has dual effects on the electrical characteristics with respect to the temperature. The PV module open-circuit voltage is almost independent of the irradiation: in literature it is stated that such a dependence is logarithmic. On the contrary, the short-circuit current is linearly dependent on the irradiance.

As a consequence of this dependence, it is mandatory to adopt an intermediate conversion stage, interfacing the PV array and the power system that processes or uses the electrical power produced thereof, which must be capable of adapting its input voltage and current levels to the instantaneous PV source MPP, while keeping its output voltage and current levels compliant with the load requirement.

Such a stage, known as Maximum Power Point Tracking controller, MPPT, must be able to perform this adaptation in the presence of time-varying operating conditions affecting the PV generator.

3.PSO-PID-PO MPPT

As well known the photovoltaic energy is a very interesting renewable energy source. However nonlinear characteristics of solar cells and low energy conversion efficiency are the main drawbacks.

To maximize the use of solar energy, maximum power tracking is necessary. The optimal operating point of the photovoltaic array is determined by driving the converter through the changing of the duty cycle of the DC-DC converter.

The most commonly used algorithms for the MPPT in PV systems are based on fixed step size which are easy to implement but the oscillation and accuracy problems are unavoidable. To overcome these drawbacks, a new PSO-based variable step size P&O algorithm is proposed. The P&O variable step size is optimized driving PID controller tuned by particle swarm optimization. The PSO selects the K_p, K_i and K_d PID parameters values that optimizes the power transfer through the DC-DC converter. The system structure block is shown in figure 6.

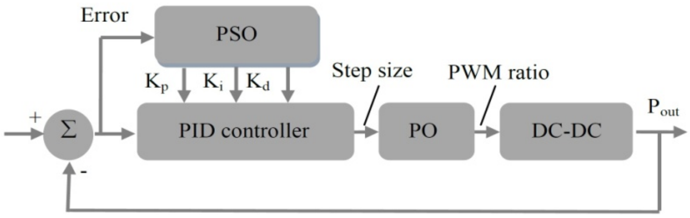

Fig. 6: The block diagram of proposed PSO based variable step size P&O MPPT

3.1 PO MPPT

Recently, many MPPT techniques have been developed and improved continuously, perturb and observe P&O method is widely applied in the MPPT controllers due to their simplicity and easy implementation.

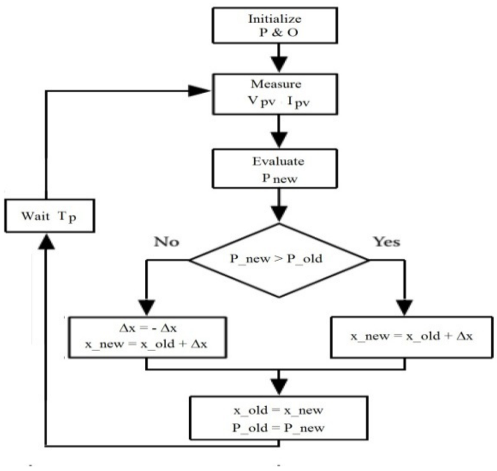

Fig. 7: Basic flowchart of the P&O method

The P&O MPPT algorithm is based on the disturbance of the output voltage $V(k)$ of the PV panel and the corresponding output power $P(k)$, which is compared with the previous perturbing cycle $P(k+1)$: if the power increases, keep the next voltage change in the same direction as the previous change. Otherwise, change the voltage in the opposite direction as the previous one; when the stable condition is reached the algorithm oscillates around the peak power point. Figure 7 shows the flowchart of the P&O method.

This method has several drawbacks such as slow tracking speed and oscillations about MPP, making it less favorable for rapidly changing environmental conditions.

Using a larger perturbation steps, the maximum power point is reached quickly, but, the power loss caused by perturbation in the steady state will also increase. With a smaller perturbation step can reduce the power loss caused by perturbation in the steady state but will slow down the tracking speed.

3.2 PSO Overview

Particle swarm optimization is a population-based swarm intelligence algorithm. It was originally proposed by Kennedy *et al.* [29] as a simulation of the social behavior of social organisms such as bird flocking and fish schooling

PSO uses the physical movements of the individuals in the swarm and has a flexible and well-balanced mechanism to enhance and adapt to the global and local exploration abilities. Because of its easy implementation and inexpensive computation, its simplicity in coding and consistency in performance, PSO has proved to be an effective and competitive algorithm for the optimization problem in continuous spaces.

Most applications of PSO have concentrated on the optimization in continuous spaces while recently some work has been done to the discrete optimization problem.

The PSO algorithm first randomly initializes a swarm of particles. The position of each individual (called particle) is represented by a d-dimensional vector in problem space $S_i = (S_{i1}, S_{i2}, ..., S_{iN})$ $i = 1, 2, ..., N$ (N is the population size), and its performance is evaluated on the predefined fitness function.

Thus, each particle is randomly placed in the d-dimensional space as a candidate solution. The velocity of the i[th] particle $v_i = (v_{i1}, v_{i12}, ..., v_{id})$ is defined as the change of its position. The flying direction of each particle is the dynamical interaction of individual and social flying experience.

The algorithm completes the optimization through following the personal best solution of each particle and the global best value of the whole swarm. Figure 8 shows PSO optimization process.

Each particle adjusts its trajectory toward its own previous best position and the previous best position attained by any particle of the swarm, namely p_i and p_g. In each iteration, the swarm is updated by the following equations:

$$\upsilon_i(t+1) = \upsilon_i(t) + c_1 \, rand_i (p_i - s_i(t)) + c_2 \, rand_2 (p_g - s_i(t)) \qquad (10)$$

$$s_i(t+1) = s_i(t) + \upsilon_i(t+1) \qquad (11)$$

where, $p_i = (p_{i1}, p_{i2}, ..., p_{iN})$ is the best position encountered by i[th] particle so-far; p_g represents the best position found by any member in the whole swarm population; t is iteration counter. c_1 and c_2 are acceleration coefficients; $rand_1$ and $rand_2$ are two uniform random numbers in [0,1].

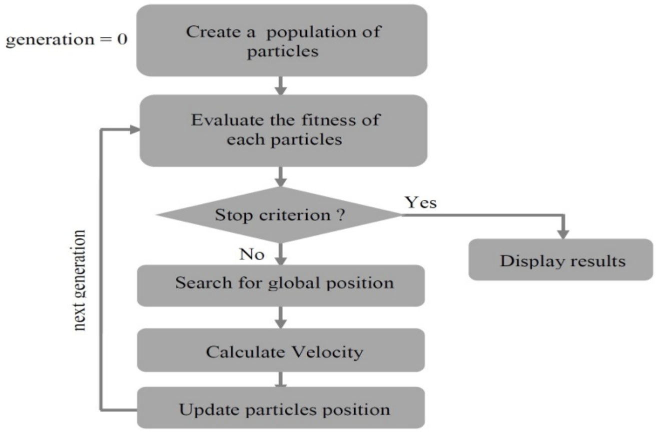

Fig. 8: Simple PSO Algorithm

The acceleration coefficients control how far a particle will move in a single iteration. Low values allow particles to roam far from target regions before being tugged back, while high values result in abrupt movement towards, or past, target regions.

In this study, we use PSO algorithm to find the optimal PID controller parameters using a fitness function based on variable step size P&O MPPT performances.

3.3 PSO-PID-PO MPPT implementation

The PID controller gains are optimized using PSO algorithm. The process of PSO optimization is described by figure 9. As objective function, we use the Integrated Absolute Error (IAE) measure defined by:

$$IAE = \int |\varepsilon| dt \tag{12}$$

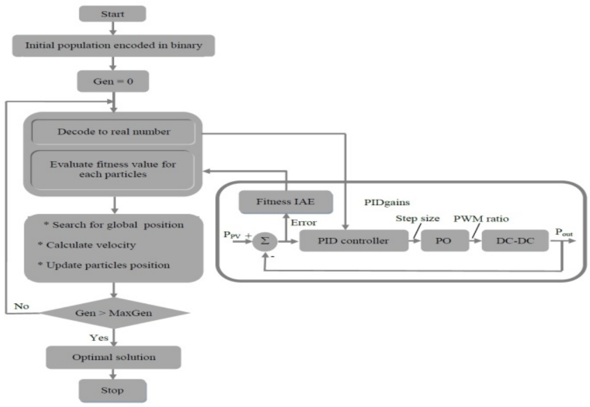

Fig. 9: PID controller gains PSO optimization process

The system operates in two modes:

1) the offline mode required for testing different set of PID controller gains to find optimum values;

2) the online mode that uses the optimum PID controller gains to track the MPP point driving the variation of the step size of the P&O MPPT algorithm.

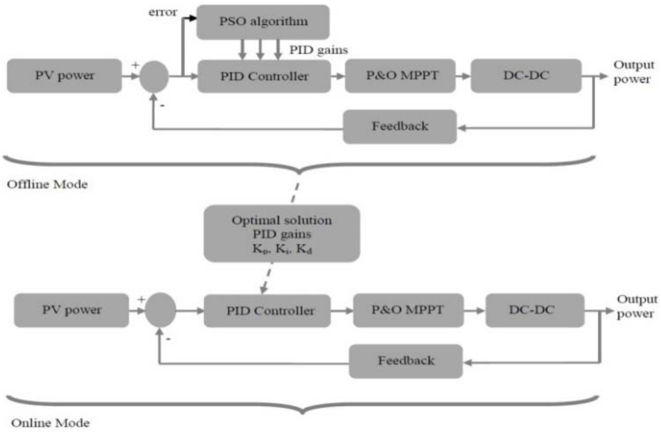

Fig. 10: Proposed system operating modes

4. SIMULATION, RESULTS AND DISCUSSION

To illustrate the effectiveness of proposed PSO-PID-PO MPPT algorithm, the model of the whole system described by figure 11 designed using Matlab/Simulink software is considered.

It is composed of PV panel operating at variable temperature and irradiation, PID controller tuned by PSO algorithm driving the variable step size needed by P&O MPPT algorithm that controls the duty cycle of DC-DC converter.

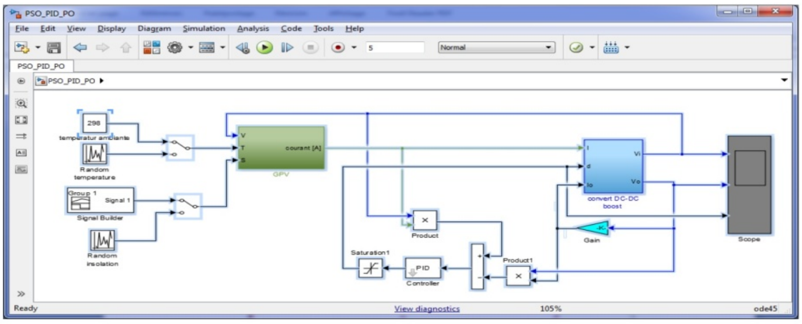

Fig. 11: Matlab/Simulink Model of the proposed PSO-PID-PO MPPT

The simulated PSO algorithm parameters used to initialize the PSO algorithm parameters and generating an initial random population of individuals representing the PID controller gains (K_p , K_i and K_d) are defined in **Table 1**.

Table 1: PSO parameters

Description	Parameters
Population size	20
Maximum iteration	50
c_1 and c_2	2 and 2

The optimum PID controller gains are given in **Table 2**.

Table 2: PSO parameters

Gain	Value
K_p	1.0230
K_i	1.1216
K_d	0.5695

Once the PID controller optimum gains fixed in offline mode, we use this controller in online mode to drive the variable step size of the P&O MPPT algorithm. The results are divided in two parts:

• **Standard tests**: representing different schemes simulating different atmospheric conditions;

• **Robustness tests**: illustrating the effectiveness of the proposed algorithm in case of: **a)** insolation variation with fixed temperature; **b)** temperature variation with fixed insolation; and **c)** variation of both insolation and temperature which is considered as the hardest test for all MPPT controllers.

4.1 Standard tests

Figure 12 shows maximum power point tracking at the output of the DC/DC boost converter corresponding to the input irradiation scheme.

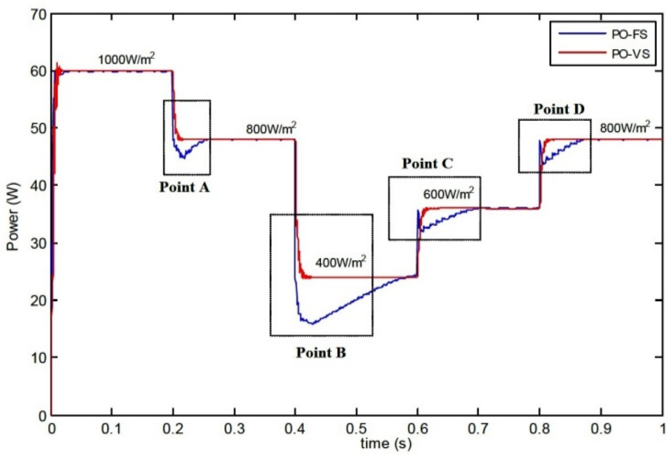

Fig. 12: MPP tracking

Point A

From figure 13, the overshoot due to irradiation changing from 1000 W/m^2 to 800 W/m^2 (Point A) is 0.16 W (0.33 %) for the proposed variable step size algorithm instead of 3.3W (6.88 %) for the fixed step size version.

The proposed algorithm shows a significant improvement in the time interval corresponding to the period of rapidly changing atmospheric conditions (30 ms instead of 60 ms).

In addition, the proposed algorithm shows a good performance in steady state (no ripple in steady state) keeping a low steady state error 0.03 W (0.06 %) instead of the ripple and oscillations around MPP for the fixed step size P&O algorithm 0.17 W (0.36%).

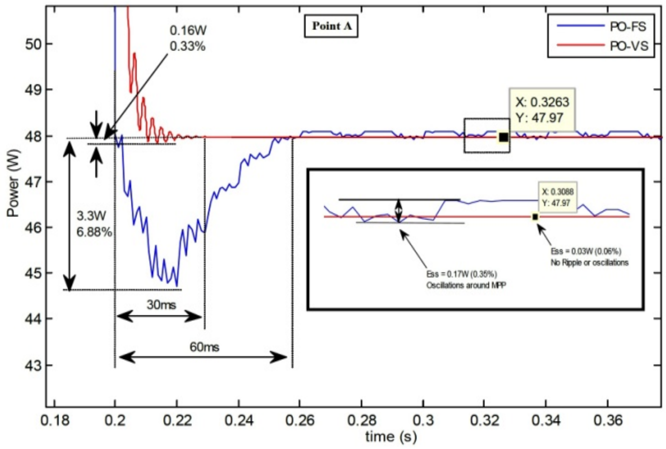

Fig. 13: Point A: insolation varying from 1000 W/m^2 to 800 W/m^2

Point B

From figure 14, the overshoot due to hard irradiation changing from 800 W/m^2 to 400W/m^2 (Point B) is more important 0.29 W (1.21 %) for the proposed variable step size algorithm instead of 8.18 W (34.08 %) for the fixed step size version.

The improvement of the response time corresponding to the period of rapidly changing atmospheric conditions is undeniably clear (43 ms instead of 180 ms).

The performance of the proposed algorithm regarding the steady state response (no ripple in steady state) keeping a low steady state error 0.06 W (0.25 %) instead of the ripple and oscillations around MPP for the fixed step size P&O algorithm 0.27 W (1.13%).

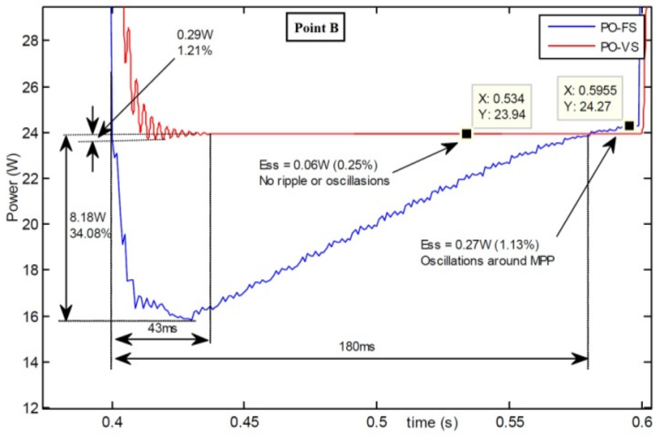

Fig. 14: Point B: insolation varying from 800 W/m^2 to 400 W/m^2

Point C

Figure 15 corresponding to an increase of the irradiation level from 400 W/m^2 to 600 W/m^2 (Point C) have the same behavior. The overshoot is 0.16 W (0.44 %) for the proposed variable step size algorithm instead of 4.10 W (11.39 %) for the fixed step size P&O algorithm.

The improvement of the response time corresponding to the period of rapidly changing atmospheric conditions is confirmed (36 ms instead of 90 ms).

The performance of the proposed algorithm regarding the steady state response (no ripple in steady state) keeping always a low steady state error 0.01 (0.03 %) instead of the ripple and oscillations around MPP for the fixed step size P&O algorithm 0.15 W (0.42 %).

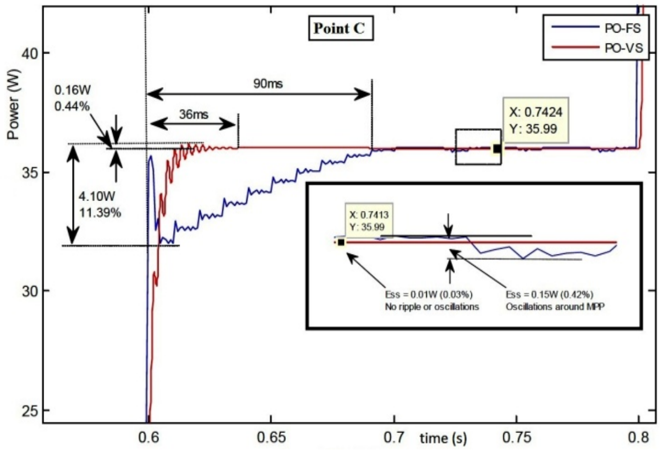

Fig. 15: Point C: insolation varying from 400 W/m^2 to 600 W/m^2

Point D

Figure 16 corresponding to an increase of the irradiation level from 600 W/m^2 to 800 W/m^2 (Point D) have the same behavior. The overshoot is 0.10 W (0.21 %) for the proposed variable step size algorithm instead of 3.35W (6.98 %) for the fixed step size P&O algorithm.

The improvement of the response time corresponding to the period of rapidly changing atmospheric conditions is always confirmed (28 ms instead of 72 ms).

The proposed algorithm regarding the steady state response, outperforms the fixed step size algorithm with no ripple or oscillations in steady state keeping always a low steady state error 0.04 W (0.08 %) instead of the ripple and oscillations around MPP for the fixed step size P&O algorithm 0.12 W (0.25 %).

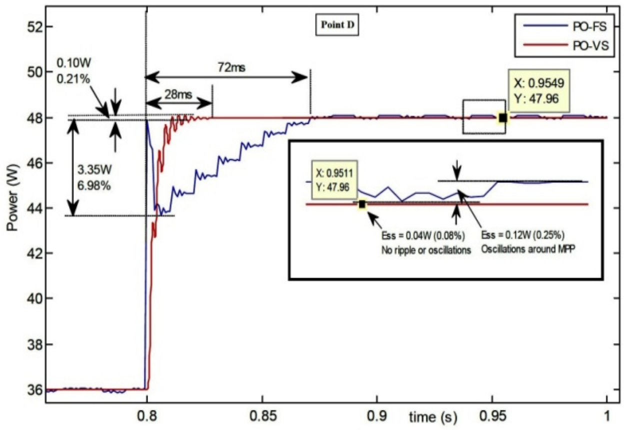

Fig. 16: Point D: insolation varying from 600 W/m^2 to 800 W/m^2

The simulation results demonstrating the main contribution of this study are summarized in **Table 3**.

Table 3: Results summary

	Overshoot (%)		Response time (ms)		Steady state error (%)	
	PO-FS	PO-VS	PO-FS	PO-VS	PO-FS	PO-VS
Point A	6.68	**0.33**	60	**30**	0.36	**0.06**
Point B	34.08	**1.21**	180	**43**	1.13	**0.25**
Point C	11.39	**0.44**	90	**36**	0.42	**0.03**
Point D	6.98	**0.21**	72	**28**	0.25	**0.08**

From **Table 3**, we can see clearly that the proposed PSO-based PID variable step P&O algorithm outperforms the fixed step size P&O algorithm in all test cases regarding the considered performance measure in dynamic and steady state responses

5.2 Robustness tests

To validate the robustness and reliability of the proposed PSO-PID-PO MPPT algorithm, we test its ability to track the MPP point in case of fast and hazardous changing atmospheric conditions making several robustness tests:

- Random insolation with fixed temperature 25°C (figure 17);
- Random temperature with fixed insolation 800 W/m^2 (figure 18);
- Random variation of both insolation and temperature (figure 19).

Figures 17 and 18 show the results obtained using the proposed algorithm for tests with one environmental parameter fixed and the other one random. Regarding the circled parts in figure, we can rapidly see that the proposed algorithm shows a significant improvement in the time interval corresponding to the period of rapidly changing atmospheric conditions.

Compared to conventional fixed step P&O tracking algorithm, the proposed PSO-PID variable step size P&O avoid oscillation around the maximum power with an accurate tracking of the MPP point. This last point has a direct impact on lost energy.

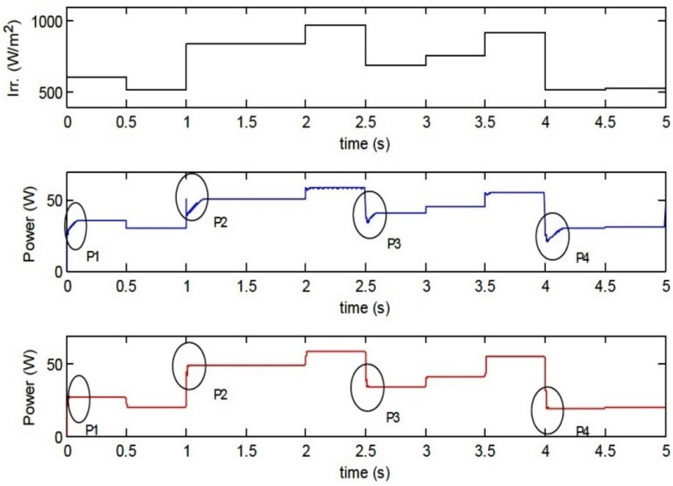

Fig. 17: Random insolation with fixed temperature (25°C).

For the third robustness test considering both insolation and temperature variation, the results obtained using the proposed PSO-PID variable step size P&O MPPT, the obtained output power is twice using this algorithm compared to the output power obtained using the fixed step size P&O algorithm which fails to track the MPP point especially in case of both variation of insolation and temperature.

The robustness tests prove the reliability and the effectiveness of the proposed PSO-PID variable step size P&O MPPT compared to the fixed step size P&O MPPT. These results show the improvement provided by the proposed algorithm in dynamic and steady state which have a direct impact on reducing the wasting power.

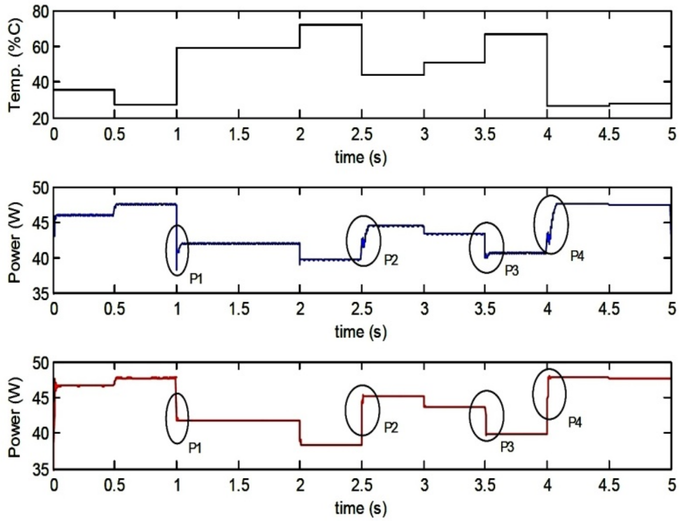

Fig. 18: Random temperature with fixed insolation 800 W/m^2)

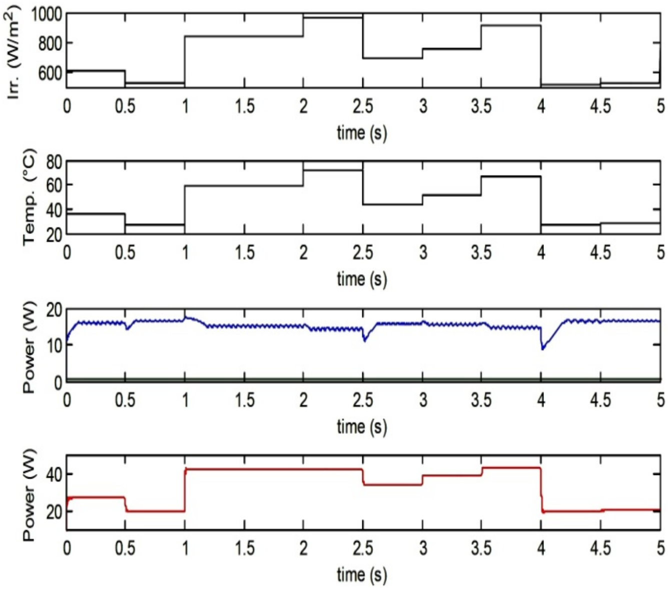

Fig. 19: Random insolation and random temperature

5. CONCLUSION

In this paper, the bio-inspired particle swarm optimization is used to find optimum gains of PID controller used to drive the variable step size of the perturbation and observe maximum power point algorithm according to index measure function combining transient and steady state performances.

The PID controllers gains are calculated firstly offline using PSO optimization. The set of optimum PID controller gains have been tested online. The proposed PSO-PID variable step-size P&O MPPT algorithmic simulated using Matlab/Simulink model, where the different aspects of the system and parameters have been implemented.

The simulation results demonstrate the effectiveness of the proposed PSO-PID variable step algorithm at the aspect of improving the accuracy, rapidity, ripple and overshoot. The robustness of the proposed PSO-PID variable step P&O algorithm is demonstrated using scheme with random irradiation.

The simulation results of the proposed PSO-PID MPPT algorithm exhibit a faster converging speed, less overshoot, no oscillation around the MPP under steady-state conditions, and no divergence from the MPP under fast varying atmospheric conditions.

In addition, the robustness tests of the proposed PSO-PID variable step size P&O MPPT under random both insolation and temperature which is considered as the hardest test for all MPPT controllers have been proved high performances and a good effectiveness.

REFERENCES

[1] L. Fangrui, D. Shanxu, L. Fei, L. Bangyin and K. Yong, '*A Variable Step Size INC MPPT Method for PV Systems*', IEEE Transactions on Industrial Electronics, Vol. 55, N°7, pp. 2622 - 2628, 2008.

[2] D. Rekioua and E. Matagne, '*Optimization of Photovoltaic Power Systems: Modelization, Simulation and Control*', Springer-Verlag, London, 2012.

[3] A. Goetzberger and V. Hoffmann, '*Photovoltaic Solar Energy Generation*', Germany: Springer; 2005.

[4] P. Bajpai and V. Dash, '*Hybrid Renewable Energy Systems for Power Generation in Stand-Alone Applications: A Review*', Renewable and Sustainable Energy Reviews', Vol. 16, pp. 2926 - 2939, 2012.

[5] A. Harrag and S. Messalti, '*Variable Step Size Modified P&O MPPT Algorithm Using GA-Based Hybrid Offline/Online PID Controller*', Renewable and Sustainable Energy Reviews, Vol. 49, pp. 1247 – 1260, 2015.

[6] Hiyama Takashi, Kouzuma Shinichi and Imakubo Tomofui, '*Evaluation of Neural Network Based Real Time Maximum Power Tracking Controller for PV System*', IEEE Transactions on Energy Conversion, Vol. 10, N°3, pp. 543 - 548, 1995.

[7] V. Scarpa, S. Buso, and G. Spiazzi, '*Low-Complexity MPPT Technique Exploiting the PV Module MPP Locus Characterization*', IEEE Transactions on Industrial Electronics, Vol. 56, N°5, pp. 1513 - 1538, 2009.

[8] P. Bhatnagar and R.K. Nema, '*Maximum Power Point Tracking Control Techniques: State-Of-The-Art in Photovoltaic Applications*', Renewable Sustainable Energy Reviews, Vol. 23, Issue C, pp. 224 – 241, 2013.

[9] Y.E. Abu Eldahab, N.H. Saad and A. Zekry, '*Enhancing the Maximum Power Point Tracking Techniques for Photovoltaic Systems*', Renewable and Sustainable Energy Reviews, Vol. 40, pp. 505 – 514, 2014.

[10] G.N. Femia, G. Petrone, G. Spagnuolo and M. Vitelli, '*Optimization of Perturb and Observe Maximum Power Point Tracking Method*', IEEE Transaction on Power Electronics, Vol. 20, N°4, pp. 963 – 973, 2005..

[11] L. Piegari and R. Rizzo, '*Adaptive Perturb and Observe Algorithm for Photovoltaic Maximum Power Point Tracking*', Renewable Power Generation, IET Vol. 4, pp. 317 - 328, 2010.

[12] K.S. Tey and S. Mekhilef, '*Modified Incremental Conductance MPPT Algorithm to Mitigate Inaccurate Responses under Fast-Changing Solar Irradiation Level*', Solar Energy, Vol. 101, pp. 333 – 342, 2014.

[13] G. Li and H.A. Wang, '*Novel Stand-Alone PV Generation System Based on Variable Step Size INC MPPT and SVPWM Control*', IEEE 6th International Power Electronics and Motion Control Conference, IEEE-IPEMC'09, pp. 2155 - 2160, 2009.

[14] A. Safari and S. Mekhilef, '*Simulation and Hardware Implementation of Incremental Conductance MPPT with Direct Control Method using Cuk Converter*', IEEE Transactions on Industrial Electronics, Vol. 58, pp. 1154 - 1161, 2011.

[15] W. Xiao and W.G. Dunford, '*A Modified Adaptive Hill Climbing MPPT Method for Photovoltaic Power Systems*', in Proc. 35th Annual IEEE Power Electronics Specialists Conference, Vol. 3, pp. 1957 – 1963, 2004.

[16] T. Esram and P.L. Chapman, '*Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques*', IEEE Transactions on Energy Conversion, Vol. 22, N°2, pp. 439 – 449, 2007.

[17] M.A. Eltawil and Z. Zhao, '*MPPT Techniques for Photovoltaic Applications*', Renewable and Sustainable Energy Reviews, Vol. 25, pp. 793 – 813, 2013.

[18] L.K. Letting, J.L. Munda and Y. Hamam, '*Optimization of a Fuzzy Logic Controller for PV Grid Inverter Control Using S-Function Based PSO*', Solar Energy, Vol. 86, N°6, pp. 1689 – 1700, 2012.

[19] T. Hiyama, S. Kouzuma and T. Imakubo, '*Identification of Optimal Operating Point of PV Modules Using Neural Network for Real Time Maximum Power Tracking Control*', IEEE Transactions on Energy Conversion, Vol. 10, N°2, pp. 360 – 367, 1995.

[20] M.A.S. Masoum, H. Dehbonei and E.F. Fuchs, '*Theoretical and Experimental Analyses of Photovoltaic Systems with Voltage and Current-Based Maximum Power-Point Tracking*', IEEE Transactions on Energy Conversion, Vol. 17, N°4, pp. 514 - 522, 2002.

[21] T. Noguchi, S. Togashi and R. Nakamoto, '*Short-Current Pulse Based Adaptive Maximum Power Point Tracking for Photovoltaic Power Generation System*', In: IEEE International Symposium on Industrial Electronics, N°1, pp. 157 - 162, 2000.

[22] G.W. Hart, H.M. Branz and C.H. Cox, '*Experimental Tests of Open-Loop Maximum Power-Point Tracking Techniques*', Solar Cells, Vol. 13, pp. 185 - 195, 1984.

[23] R. Ramaprabha, V. Gothandaraman, K. Kanimozhi, R. Divya and B.L. Mathur, '*Maximum Power Point Tracking using GA-Optimized Artificial Neural Network for Solar PV System*', 1 st International Conference on Electrical Energy Systems, 'ICEES', pp. 264 - 268, 2011.

[24] C. Larbes, M.S.. Cheikh, T. Obeidi, and A. Zerguerras, '*Genetic algorithms optimized fuzzy logic control for the maximum power point tracking in photovoltaic syste*m, Renewable Energy, Vol. 34, pp. 2093 - 2100.

[25] A. Al-Diab and C. Sourkounis, '*Variable Step Size PO MPPT Algorithm for PV Systems*', In: Proceedings of Optimization of Electrical and Electronic Equipment, OPTIM Conference, pp. 1097 - 1102, 2010.

[26] N. Vázquez, Y. Azaf, I. Cervantes, E. Vázquez and C. Hernández, '*Maximum Power Point Tracking Based on Sliding Mode Control*', International Journal of Photoenergy, 2015, in press.

[27] F. Zhang, J. Maddy, G. Premier and A. Guwy, '*Novel Current Sensing Photovoltaic Maximum Power Point Tracking Based on Sliding Mode Control Strategy*', Solar Energy, Vol. 118, pp. 80 - 86, 2015.

[28] N. Femia, G. Petrone, G. Spagnuolo and M. Vitelli, '*Power Electronics and Control Techniques for Maximum Energy Harvesting in Photovoltaic* Systems', London, U.K.: Taylor & Francis, 2003.

[29] J. Kennedy and R. Eberhart, '*Particle Swarm Optimization*', In Proceedings of 1995 IEEE International Conference on Neural Networks, Vol. 4, pp.1942 – 1948, 1995.