

A Real-Time PSO MPPT Strategy Combined with Backstepping Control for Grid Connected Photovoltaic System

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Abstract— This paper considers the problem of controlling a single-phase grid-connected photovoltaic (PV) system using a Particle Swarm Optimization (PSO)-based MPPT strategy combined with a nonlinear backstepping controller. The system consists of a PV panel, a DC–DC boost converter, a half-bridge DC–AC inverter, and an L filter for grid connection. The proposed approach aims to achieve three main objectives: maximum power extraction from the PV system, unity power factor operation by ensuring a sinusoidal grid current in phase with the grid voltage, and stable DC-link voltage regulation. The stability of the overall control scheme is analyzed, and the effectiveness of the proposed method is evaluated through MATLAB/Simulink simulations and validated using a Processor-in-the-Loop (PIL) implementation.

Keywords— PSO Algorithm, MPPT, PV System, Processor-in-the-Loop, Backstepping

I. INTRODUCTION

The demand for electrical energy is increasing day by day, and this energy is largely produced via fossil fuels which represents many disadvantages. However, a transition to green energy is necessary. Currently, several renewable energy sources are used in the development of the energy sector due to their clean and sustainable characteristics. However, in this article, the exploitation of photovoltaic (PV) energy turns out to be an ideal solution, as it is abundant given the geolocation of the country, renewable and free. In order to exploit the photovoltaic panels to the power grid, a matching stage is required to achieve two main objectives: extracting the maximum power and injecting the current with a unity power factor [1]. For optimize the power generation efficiency of photovoltaic panels, MPPT technology has attracted several research works. Therefore, it is crucial to propose a suitable MPPT control method [2]. However in this paper we propose the use of the PSO (Particle Swarm Optimization) algorithm. PSO, inspired by nature and more precisely by the collective behavior of swarms [3], is a robust optimization method that dynamically adjusts the reference voltage. To connect the conversion system with the grid, inverters are used. Adaptive approaches for AC and DC systems have also been explored in the literature. For example, [4] introduced a sliding mode controller (SMC) combined with an adaptive observer to improve the robustness and performance of the system with INC algorithm. Similarly, [5] proposed a control law using the backstepping approach to stabilize the overall system with a P&O algorithm. The work reported in this paper focuses on the analysis of a grid-connected PV system using a PSO algorithm to ensure maximum power point tracking and a nonlinear controller based on the Backstepping technique to ensure the control objectives. The system integrates three control loops: i) maximum power point tracking (MPPT) using the PSO algorithm, ii) regulating the DC bus voltage, iii) obtaining a unity power factor in order to inject a current in phase with the voltage into the grid.

II. SYSTEM DESCRIPTION AND MODELING

A. System Description

The structure of the single-phase PV-powered power conversion system, as shown in Figure 1, the DC section comprises a PV panel connected to a DC-DC boost converter, controlled by the inputs $\mu_1 \in \{0,1\}$, while the AC section, which serves as an interface with the single-phase grid, consists of a half-bridge inverter controlled by the inputs $\mu_2 \in \{-1,1\}$, with an L filter. The commutations are governed by the pulse-width modulation (PWM) technique.

B. System Modelling

Using the standard Kirchoff laws, the switched model of the single-phase half-bridge PV system can be obtained, as follows:

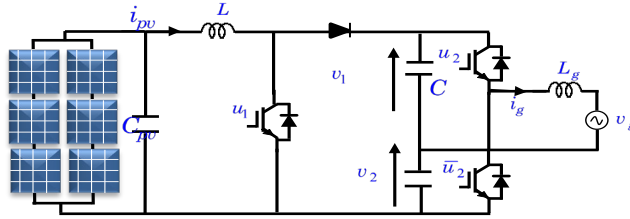


Fig. 1 Structure of the studied system.

$$C_{pv} \frac{dv_{pv}}{dt} = \overline{i_{pv}} - i_l \tag{1.a}$$

$$L \frac{di_l}{dt} = v_{pv} - (1 - \mu_1)(v_1 - v_2) \tag{1.b}$$

$$C \frac{dv_1}{dt} = (1 - \mu_1)i_l - \frac{(1-\mu_2)}{2}i_g \tag{1.c}$$

$$C \frac{dv_2}{dt} = (1 - \mu_1)i_l - \frac{(1 - \mu_2)}{2}i_g \tag{1.d}$$

$$L_g \frac{di_g}{dt} = -r_g i_g + \frac{(1 + \mu_2)}{2}v_1 - \frac{(1 - \mu_2)}{2}v_2 - v_g \tag{1.e}$$

With i_{pv} is the PV current, v_{pv} the PV voltage, v_1 and v_2 are the capacitor voltages, i_l is the inductor current, r_g is the equivalent series resistance of inductance L_g . Let's put: $v_1 + v_2 = v_o$ and $v_1 - v_2 = v_d$

Or in this model μ_1 and μ_2 are a binary control inputs, therefore, it is not suitable to be based upon them while designing continuous control laws. To solve this problem, it is usually resorted to the average model

$$C_{pv} \frac{dx_1}{dt} = \overline{i_{pv}} - x_2 \tag{2.a}$$

$$L \frac{dx_2}{dt} = x_1 - (1 - u_1)x_3 \tag{2.b}$$

$$C \frac{dx_3}{dt} = 2(1 - u_1)x_2 - u_2x_5 \tag{2.c}$$

$$C \frac{dx_4}{dt} = -x_5 \tag{2.d}$$

$$L_g \frac{dx_5}{dt} = -r_g x_5 + \frac{1}{2}x_4 - \frac{u_2}{2}x_3 - v_g \tag{2.e}$$

TABLE 1. AVERAGE VALUES OF MODEL

Parameter	symbols	average values
PV voltage	v_{pv}	x_1
PV Current	i_{pv}	$\overline{i_{pv}}$
Inductor current	i_l	x_2
Sum voltage of v_1 and v_2	v_o	x_3
Differential voltage of v_1 and v_2	v_d	x_4
grid current	i_g	x_5
Binary input control	μ_1	u_1
Binary input control	μ_2	u_2

III. PARTICLE SWARM OPTIMIZATION ALGORITHM FOR MAXIMUM POWER POINT TRACKING

The goal of MPPT algorithms is to maximize the power extracted from photovoltaic (PV) panels. In this work, the Particle Swarm Optimization (PSO) algorithm is used. It is an intelligent algorithm widely used

in various optimization problems. This algorithm is inspired by nature, and more precisely by the collective behaviors of swarms, such as birds or fish gathering together [3] [6]. The PSO algorithm, is based on randomly distributed particles in the M-dimensional search space [7] [8], whose $X_i=(x_{i1}, x_{i2}, \dots, x_{iM})$ is a solution to the optimization problem in the M-dimensional space, corresponding to the position of the i^{th} particle in the particle swarm. While $P_{ibest}=(p_{i1}, p_{i2}, \dots, p_{iM})$ is considered as the optimal position on all paths traveled by the i^{th} particle, it is the best local optimal solution sought. However, $G_{best}=(G_{best1}, G_{best2}, \dots, G_{bestm})$ represents the optimal position on the path traveled by all the particles, it means the global optimal solution. $V_i=(v_{i1}, v_{i2}, \dots, v_{im})$ is the velocity of the particle. Relations represent by (3) and (4) are the main formulas of the PSO, and particles update their positions and velocities using these two formulas.

$$v_{i+1} = w * v_i + c_1 \text{rand}_1(P_{best} - x_i) + c_2 \text{rand}_2(G_{best} - x_i) \quad x_{i+1} = x_i + v_i \quad (3)$$

(4). To apply this algorithm

shown in figure 2, in the context of MPPT, each particle in the swarm represents a value of the candidate voltage, and its fitness function corresponds to the output power of the PV system. The particles iteratively adjust their positions (voltages) according to their own best performance (Pbest) and the best overall performance observed within the swarm (Gbest). This approach promises convergence and better adaptability to dynamic environmental changes, such as variations in solar irradiance and temperature. Compared to conventional MPPT methods such as Perturb and Observe (P&O) or Incremental Conductance, the PSO algorithm offers improved accuracy and stability, especially under non-uniform climate conditions. The flow chart of the PSO is shown in figure 2. Below is the table with the exact parameters and their values based on simulation using Simulink/Matlab

TABLE 2.
PARAMETERS AND ITS VALUES FOR PSO ALGORITHM

Parameter	Symbol	Description	Value
Number of particles	N	Total number of particles in the swarm.	10
Maximum iterations	Iter _{max}	Maximum number of iterations for convergence.	100
Cognitive coefficient	c1	Weight for personal best position influence.	2
Social coefficient	c2	Weight for global best position influence.	2
Inertia weight	w	Balances exploration and exploitation (adjusts velocity).	0,7

IV. CONTROLLER DESIGN

A. Grid current and DC-link Regulator

To achieve the above-mentioned control objectives, a controller using the Backstepping control technique and studying the stability with Lyapunov method. This approach ensures robust performance by adapting to system and network variations while maintaining precise control. The inner loop provides power factor correction (PFC). The outer loop, on the other hand, consists of a filtered PI regulator, responsible for maintaining the DC bus voltage at the desired reference, thus ensuring the stability and precision of the system. This maintains efficient power transfer and minimizes harmonics. The goal of the controller is to force the grid current x_5 to follow a reference signal as $x_5^* = \beta e_g$ (5).

After develop the analyse, one obtains the following control law: $u_2 = \frac{2}{x_3} \left(r_g x_5 - \frac{1}{2} x_4 + e_g + L_g x_5^* - c_1 z_1 \right)$ (6). It is necessary to design a control law for β , ensuring regulation of the DC bus voltage. This control law will be based on a **filtered PI** regulator and is

expressed as: $\beta = \left(\frac{c_6}{c_6 + s} \right)^3 (-k_p e - k_i \int e dt)$ (7). Where $e = x_3^2 - (x_3^*)^2$ is the error between the actual squared voltage and the reference squared voltage and $k_p > 0$ and $k_i > 0$ are the proportional and integral gains, respectively.

Theorem: Consider the closed-loop control system composed of the system dynamics described by equations (2d-e), the control law defined in (6) and (7). The global dynamics of the closed-loop system is governed by equations above. Under these conditions, the closed-loop system is globally asymptotically stable with respect to the Lyapunov functions defined.

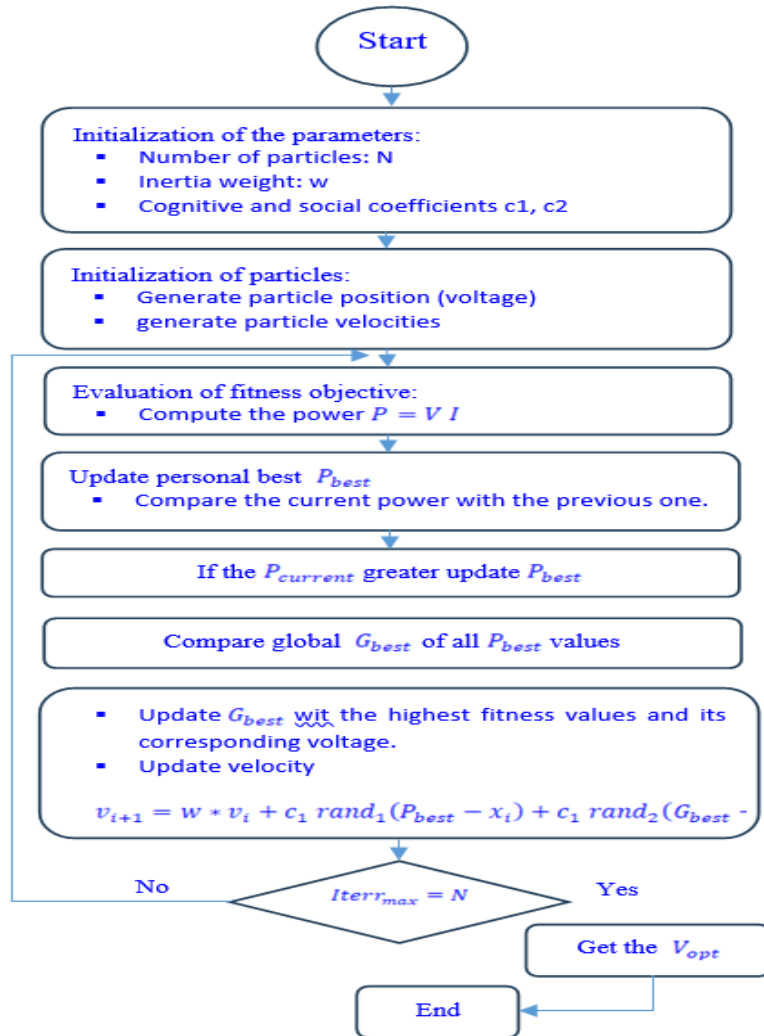


Fig 2. Particle Swarm Optimization Flow Chart.

B. Grid current and DC-link Regulator

The control law of the DC/DC boost converter is developed using the backstepping control technique with a MPPT block using the PSO optimization algorithm. The main objective of this controller is to ensure that the voltage generated by the PV system accurately follows the reference voltage provided by the PSO algorithm. Let define the set of error like $e_1 = C_{pv}(x_1 - x_1^*)$ and $e_2 = L(x_2 - x_2^*)$. Equations (2a-b) of the average system model describe the PV-Boost subsystem, and are used to derive the control law, where u_1 represents the actual control input. The Backstepping technique will be used in two sequential steps. These steps analyze the system dynamics to ensure robust voltage regulation while maintaining stability and

performance. The final expression for the control law is expressed as follows

$$u_1 = 1 + \frac{Lx_2^* - x_1 - \lambda_2 e_2 + \frac{e_1}{L}}{x_3} \quad (8)$$

This control law effectively ensures that the error variables (e_1, e_2) converge to zero, stabilizing the subsystem and guaranteeing that the system's output accurately follows the reference trajectory.

V. RESULTS OF THE PIL EXPERIMENT

The efficiency of PSO Algorithm and nonlinear controller proposed for Single-Phase Grid-Connected Photovoltaic System is investigated by processor in the loop (PIL) experiment using eZdsp controller board of Texas Instrument (Fig.3) in parallel with MATLAB/Simulink. The PIL test was conducted under two

conditions test and with a sampling frequency of 10 kHz. The parameters used in this experiment are shown in Table 3.

TABLE 3
CHARACTERISTICS OF THE CONTROLLED SYSTEM AND CONTROLLER PARAMETERS

Parameter	Symbol	Value
PV array	Power, Module	213.15W, <i>1STH-215-P</i>
DC/DC converter	L, C _{pv}	2Mh, 4mF
DC/AC converter	C	4mF
PWM	Switching frequency	10kHz
Grid	AC Source, L _g , r _g	220V, 10Mh, 0.7Ω

Parameter	Symbo l	Value
Voltage Regulator	λ_1, λ_2	10 ³
PFC Regulator	c_3, ρ	10 ⁴ , 40
DC Link regulator	k _p , k _i	10 ⁻⁶ , 4*10 ⁻⁷

The control structure is illustrated in Figure 4, providing a comprehensive overview of the system's design and functional interactions.

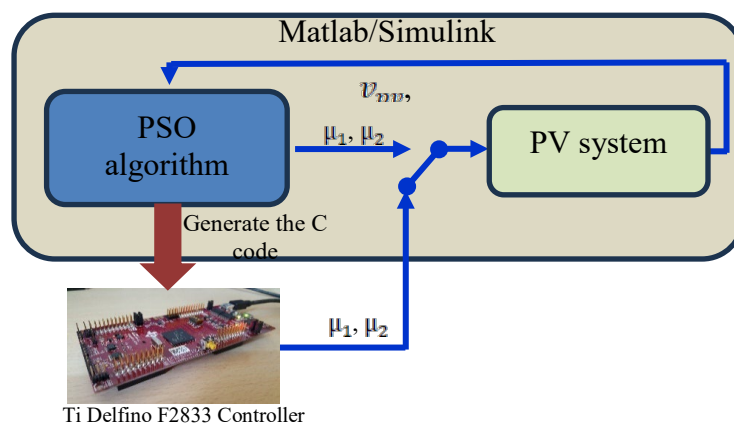


Fig 3. Block diagram of the PIL implementation process.

A. Standard Climatic Conditions

Figure 5 showing that the voltage generated by the PV panels accurately follows its reference determined from PSO algorithm. The use of PSO guarantees better performances compared to previously used algorithms [5]. Figure 6 shows that measured DC bus voltage converges to the desired reference level of 900 V. The output voltage ripples shown in the figure oscillate at a frequency of $2\pi f_g$, but their amplitudes remain negligible compared to the average value of the signal, which ensures smooth and reliable operation of the system. Figure 7 shows that the grid current converges to the desired reference and Figure 8 shows that the grid current and the network voltage are sinusoidal and in phase. This proves that the correction of the power factor is well established.

B. Temperature Variation Mode

The control performance of the entire system is evaluated under sudden changes in solar temperature. During the simulation, the temperature level increases abruptly from 25°C to 35°C. In Figure 9 it is clearly seen that thanks to the particle swarm optimization (PSO) algorithm, the controller ensures that the PV voltage accurately tracks the maximum power point, even under large variations in temperature levels.

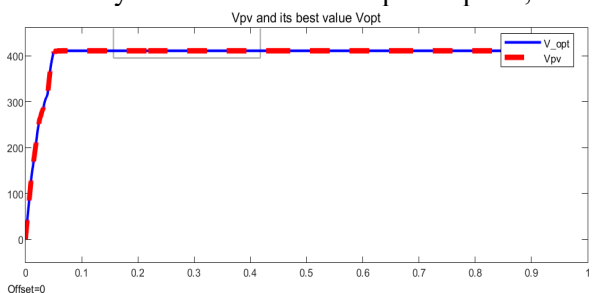


Fig 5. PV voltage output and its PSO reference

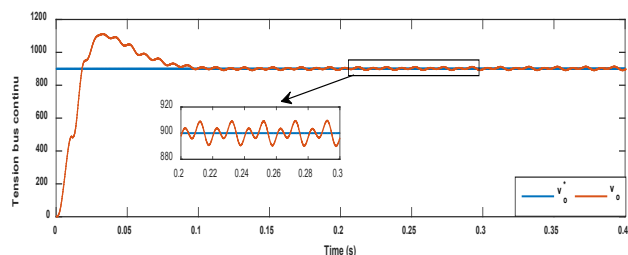


Fig 6. DC link voltage and the reference

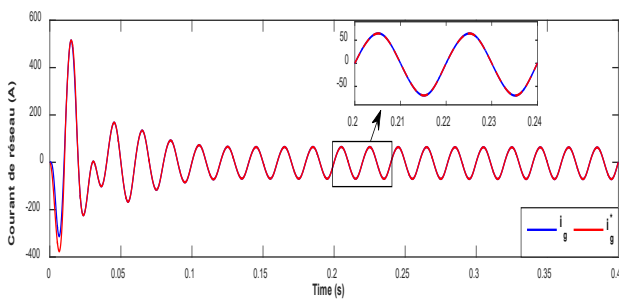


Fig 7. Grid current and its reference

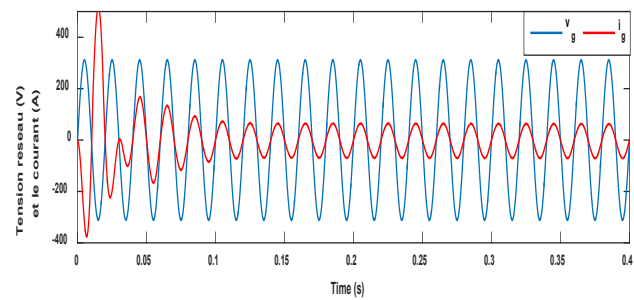


Fig 8. grid current and Voltage

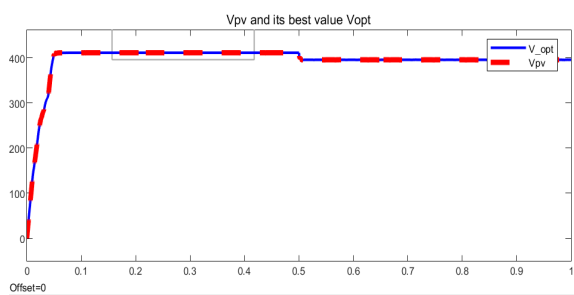


Fig 9. PV voltage output and its PSO reference

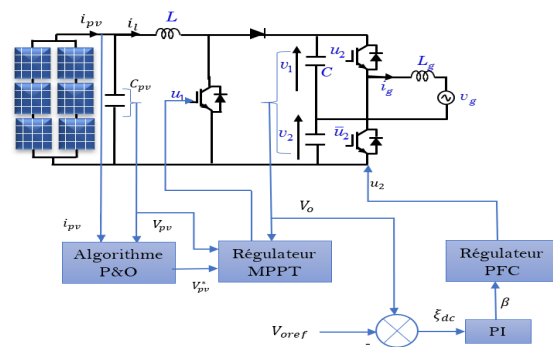


Fig 4. Control Structure.

VI. CONCLUSION

In this work, we addressed the nonlinear control problem of a PV system connected to a single-phase grid via a half-bridge inverter using the PSO algorithm for the MPPT. The main control objectives were to achieve the overall maximum and maintain it through the PSO algorithm even under variable climatic conditions, correct the power factor, and regulate the DC bus voltage. The system is modeled with an 5th-order mean-state model. The MPPT was developed by the particle swarm optimization (PSO) algorithm. Experimental validation was carried out using the PIL, and the results obtained match the simulation results, which allows the work to be validated

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