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Particle swarm optimization based sliding mode control for maximum power point tracking in solar PV systems

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ABSTRACT

One of the most significant renewable energies is photovoltaic (PV) energy, however it has a low efficiency due to its variable maximum power point that depends on weather conditions. In order to guarantee the system's best performance, intelligent algorithms can effectively track this point in real-time utilizing the maximum power point tracking (MPPT) method. Consequently, it is crucial to maximize the use of the solar energy that has been captured as well as the PV system's generated electricity. Variations in solar irradiance affects the amount of electric energy obtained from solar arrays. For efficient extraction of electricity from solar PV systems, MPPT algorithms are required. Sliding mode control (SMC) can be used in the control of nonlinear systems. However, the effectiveness of SMC can be improved by the choice of the sliding coefficients. In this paper, optimal search using particle swarm optimization (PSO) is used in the design of the sliding manifold. Results obtained via simulations showed that MPPT tracking efficiencies obtained for the PSO based SMC and the conventional SMC are 99.65% and 96.79% respectively. That means, PSO based SMC is 2.86% better than conventional SMC.

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1. INTRODUCTION

Solar energy is considered to be a key source of renewable energy and its position keeps on growing. However, solar radiation is affected by metrological variables such as ambient temperature, humidity, sunshine ratio and cloud cover. These factors have effects on the output power generated by the photovoltaic (PV) system. The electricity generated by PV arrays varies continuously with weather. The PV cell current-voltage i.e. I-V characteristics varies nonlinearly with temperature and irradiance [1]. On the voltage-current(V-I) or voltage-power (V-P) curve of the PV system, there exists a point at which maximum power output power is generated. This point is referred to as the maximum power point (MPP). The location of the MPP is not known and also varies with environmental conditions. For optimal harvesting of solar power, the MPP has to be located. Maximum power point tracking is used to keep the solar arrays' operating point at its MPP [2]. What the MPPT algorithm does is that it modulates the point of operation of the PV array so that it adjusts to changes in exogenous conditions, enabling it to produce its maximum power [3].

Typically, maximum power point tracking (MPPT) algorithms are implemented with switch mode power electronic converters [4], [5]. The MPPT is basically a system that consists of two vital components: a DC-DC power electronic converter topology and with a control algorithm for MPPT. By modulating the switching duty ratio, the goal of the tracking process is to match the load impedance R_L and the input impedance of the converter seen by the solar array R_i rarely match since these parameters hardly match [6]–[9]. MPPT schemes have been proposed in the literature. These includes perturb and observe (P&O) method [10], the incremental conductance (IC) method [11], extremum seeking control (ESC) [12], [13], ripple correlation control (RCC) [14], [15]. The P&O and IC methods have been very popular. The P&O is considered the workhorse MPPT algorithm mainly due to its combination of simplicity and performance. In terms of its basic working principle, P&O achieves MPPT by observing the output power following the perturbation of the control input in a given direction. If the power is increasing, the perturbation direction is unchanged, whereas if the power is decreasing, the direction is reversed. Due to its use of fixed perturbation size, the standard P&O method suffers from a performance tradeoff between rise-time and steady-state performance. Although the P&O has the advantage of simplicity, the algorithm falls short in speed and the adaptability required for tracking irradiance with fast transients. It has also been shown that P&O tracks in the wrong direction given rapidly varying solar irradiance [4], [16]. It has also been shown that under fast varying solar irradiance, P&O fails to track in the right direction.

Sliding mode control has been used in the control of nonlinear systems such as DC-DC converters [17], [18]. Major reported advantages of SMC include stability, robustness against parameter variations, fast dynamic response and implementation simplicity. However, the dynamics of the sliding mode (SM) controller is affected by the choice of parameters (sliding coefficient) for constructing the sliding surface or sliding manifold. The equivalent sliding manifold defined from the choice of sliding coefficient (control parameters) determine the behavior (e.g. it remains on the sliding surface and without the chattering problem) of the controlled trajectory especially its convergence at the equilibrium point. In this paper, a variant of the SM control is proposed for MPPT in which optimal search technique is exploited in the selection of the parameters of the sliding surface of the SM controller. For this, particle swarm optimization technique is used for the selection of optimal sliding coefficients in the design of the SMC for tracking the MPP of solar arrays via switched mode power converter interfaces. The SMC obtained based on this approach is referred to, in this paper, as the PSO based SM controller, whereas the standard SMC is referred to as the conventional sliding mode control/controller.

PSO algorithm is a population-base optimal search technique originally developed by Kennedy and Eberhart in 1995 [19]. This optimization algorithm falls into the category of swarm intelligence (SI) algorithms. It was motivated by the social behavior of group organisms, such as bird flocking or fish schooling. In PSO, the potential solution to a problem is represented by the position value of particles. Due to its effectiveness in performing difficult optimization tasks, PSO has been used in performing difficult optimization tasks. Furthermore, the algorithm obtains better results faster and cheaper compared to several other methods with fewer parameters to adjust. Application areas where it is applied include multi-objective optimization problems [20]–[23], min-max problems [24], [25], integer programming problems [24], combinatorial optimization problems [26], [27], clustering and classification problem and numerous other areas especially engineering applications [28]–[30].

2. THE BUCK CONVERTER MODEL

In this paper, the buck converter is used as DC-DC converter to interface the PV array with the load. This device is modulated to provide the power conditioning for the regulation of the MPPT. Here, as in most applications, this power converter is controlled via PWM of which the required duty cycle control input is generated by the proposed PSO based sliding mode controller. Figure 1 shows the schematic diagram of the controlled buck converter. For the mathematical model of the SM controlled buck converter, the state space description of the converter is ideal [31], [32]. For the model derivation, in this paper, the error in the voltage output and the voltage dynamics are used as the control parameters. As shown in Figure 1, the power interface is controlled using SMC for which sliding manifold coefficients are obtained using PSO. The converter is assumed to operate under continuous conduction mode (CCM). Taking β to be the voltage divider ratio, $\beta = \frac{R_2}{R_1+R_2}$ compared to r_L(instantaneous load resistance), the values for R_1 and R_2 are from PV generator, V_0 is the output or load voltage, D is the free- wheeling diode, $u = 1$ or 0 is the state switch S_W. Here, $u = 1$ means S_W is ON (closed) and $u = 0$ means SW OFF (open).

With reference to the diagram, the voltage error x_1 can be experienced as shown in (1).

$$x_1 = V_{ref} - \beta V_0 \tag{1}$$

Where V_{ref} is the reference voltage and βV_0 is instantaneous sensed output voltage dynamics (the rate of change of voltage error) $x_2$is expressed in (2).

$$x_2 = \dot{x_1} - \beta \frac{dV_0}{dt} = \frac{-\beta}{C} i_c \quad (2)$$

Based on Kirchoff current law (KCL) which is expressed in (3).

$$i_c = i_L - i_r \quad (3)$$

Where i_c and i_r are the capacitor current and inductor current respectively. x_2 can be expressed in (4).

$$x_2 = -\frac{\beta}{C}(i_L - i_r) \quad (4)$$

Let the instantaneous voltage drop across the inductor be expressed in (5) that implies in (6).

$$V_L = (uV_i - V_o) = L\frac{dL_i}{dt} \quad (5)$$

$$i_L = \int \frac{uV_i - V_o}{L} dt \quad (6)$$

Hence, the voltage error dynamics, x_2, can be rewritten in (7) as:

$$x_2 = \dot{x_1} = \frac{\beta}{C}(\frac{V_o}{r_L} - \int \frac{uV_i - V_o}{L} dt) \quad (7)$$

Where C and L are the capacitance and inductance respectively. By differentiating (7) with respect to time, the converter's state space model can be expressed in (8).

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{1}{LC} & -\frac{1}{r_L C} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{\beta v_1}{LC} \end{bmatrix} u + \begin{bmatrix} 0 \\ \frac{V_{ref}}{LC} \end{bmatrix} \quad (8)$$

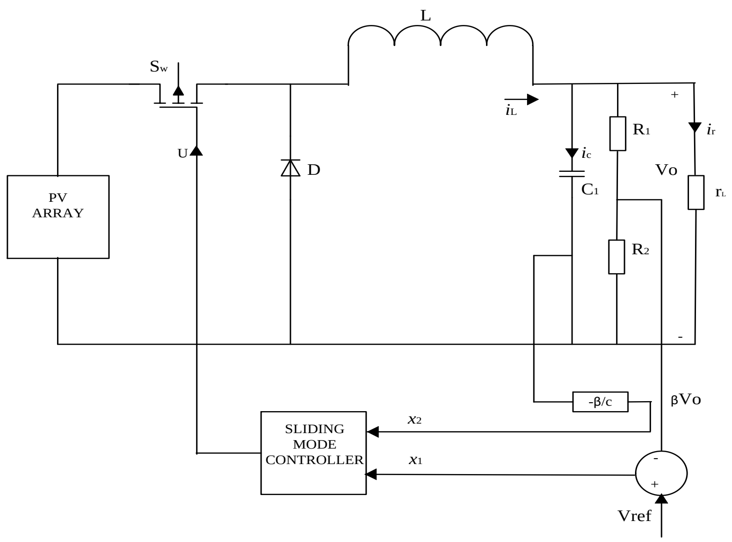

Figure 1. Schematic diagram of the controlled buck converter

3. BRIEF GENERAL THEORY OF SLIDING MODE CONTROL

Imagine the existence of a plane in 3-dimensional space. There is an equilibrium point on this plane towards which it is "desirable" to drive the state trajectory of a system. A trajectory is strongly attracted to it and eventually comes to rest on it [33]. Consider an arbitrary location, away from the said plane, of a trajectory controlled by the system. Without injecting control actions, the system's intrinsic characteristics determine the movement of its' state trajectory. However injecting control action, would alter the system's state in a desired direction. The system can be given "appropriate" sequence of control actions that first moves the controlled trajectory towards the plane, and reaching it, will slide along it towards and eventually settling upon the equilibrium point o. this should happen irrespective of its initial conditions [33].

A control scheme matching this description is referred to as SMC. The reference path which guides the trajectory is the plane. This plane is referred to as the sliding plane or sliding surface, or more generally, the sliding manifold. Figure 2 illustrates this control concept. It should be understood from Figure 2(a) that irrespective of its' initial position, the state trajectory will be driven toward the sliding manifold by the controller.

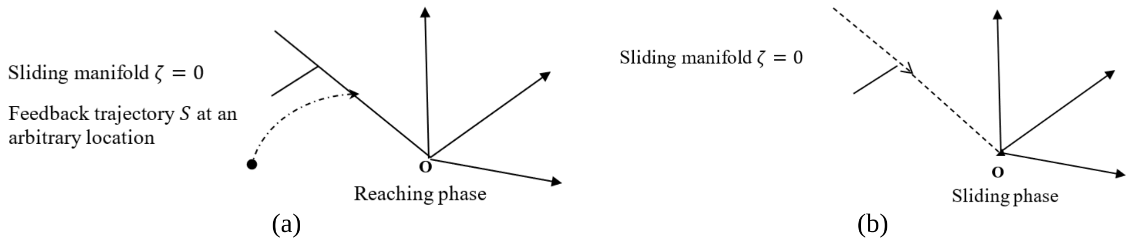

Figure 2. Illustration of the SMC concept: (a) depicts the motion of S toward the plane (i.e. the reaching phase) and (b) depicts S sliding on the plane and coming to a stop at O [32]

This is the reaching phase. This would be brought about via compliance with what is called the hitting condition [32]. Figure 2(b) shows the system sliding phase starts at the instant Sreaches the plane, at this phase the system is said to be in SM operation. At this stage an infinite sequence of switching actions is required to keep trajectory on the sliding manifold. As is indicated, the control action maintains the trajectory on the plane while moving towards settling at the equilibrium point. The existence condition has to be satisfied as part of this process. The fundamental principal of SM control law is to obtain a sliding manifold that directs the state trajectory towards a desired operating point. For the determination of its input states, the controller uses a switching function [32], [34]. For a DC-DC converter with singe switch, the control law having the following switching function u in (9) can be adopted as:

$$u = \frac{1}{2}(1 + Sign\ (S)) \tag{9}$$

Where u represents the logic state of the converter's switch s_w. From the control parameters x_1 and x_2, trajectory computation can be used to determine the switching function u, for the SM control of theconverter. Let the instantaneous state trajectory S be defined in (10) as:

$$S = \alpha x_1 + x_2 = J_x \tag{10}$$

Where α is the sliding coefficients (control parameters) which controls the first order dynamics of eq. (10); $J = [\propto, 1]$; and $x = [x_1, x_2]^T$. A sliding manifold can be derived by constraining $S = 0$ [35]. The sliding coefficient must be chosen such that the hitting, existence and stability conditions of the SM process is satisfied.

The control law can be expressed in (11) provides the general requirement that the state trajectory will be driven toward the sliding line (i.e. complying with the hitting condition). The system trajectory reaches the sliding line if the hitting (reaching) condition is satisfied. The control law triggers the switching across the sliding manifold. The required condition to meet the hitting condition is that the action $u_i = u(t > 0)$ gives a state variable vector $x(t > 0)$ that produces a trajectory $S(t > 0)$ satisfying the following inequality in (12) [32].

$$u = \begin{cases} 1 = 'ON'\ when\ S > 0 \\ 0 = 'OFF'\ when\ S < O \end{cases} \tag{11}$$

$$S_{dt}^{ds} < 0\ (for\ t > 0 \text{ and that } |s| \geq \delta) \tag{12}$$

Where δ is a point, within the neighborhood of the sliding surface, the trajectory was driven to by the resulting corresponding control action (s) $u_i = u(t > 0)$.

There has to be a guarantee that the trajectory can be kept on the sliding plane. To ensure that the trajectory is maintained on the sliding line, the existence condition must be satisfied [32], [34]. The determination of the existence condition can be achieved by inspecting only the local reachability condition expressed in (13)-(15) as (13) [34].

$$S_{dt<0}^{ds} \tag{13}$$

Such that withing the bound: $0 < |s| < \delta$, the condition must be satisfied.

$$\lim_{s \to 0} S_{dt}^{ds} < 0 \tag{14}$$

This is expressible as (15).

$$\lim_{s \to 0} \frac{ds}{dt} < 0 \text{ and } lim_{dt}^{ds} > 0 \tag{15}$$

By substituting the derivative with respect to time in (10), the existence condition is:

$$S = \begin{cases} Jx < 0\, for\ 0 < s < \xi \\ Jx > 0\, for - \xi < S < 0 \end{cases}$$

where ξ is a small number. Substituting the state space model of the buck converter in (8) and (11) into (11), the simplified existence condition for the buck coverer can be expressed in (16)-(18) as the inequalities:

$$\lambda_1 = (\alpha - \frac{1}{r_L C})x_2 - \frac{1}{LC}x_1 + \frac{V_{ref} - \beta V_i}{LC} < 0 \tag{16}$$

$$\lambda_2 = (\alpha - \frac{1}{r_1 C})x_2 - \frac{1}{LC}x_1 + \frac{Vref}{LC} > 0 \tag{17}$$

where $\lambda_1 = J_{\dot{x}}\, for\ o < s < \xi$

$$\lambda_2 = J_{\dot{x}}\, for\ -\xi < s < o \tag{18}$$

These two inequalities express the simplified existence conditions for the buck coverer.

Concurrently, the selected sliding coefficient must satisfy the stability condition along with the other conditions. This condition can be satisfied by choosing sliding coefficients that meet desired dynamical response of the buck converter (the system) [34]. The (19) shows relationship between the sliding coefficient and the dynamical response of the buck converter which can be easily obtained by substituting $s = 0$ in (10):

$$\alpha_1 x_1 + \propto_2 \frac{dx_1}{dt} = o \tag{19}$$

The inequalities giving the conditions for the hitting and existence of SM operation gives the range of applicable coefficients that keeps the buck converters response in SM operation when its trajectory is near the sliding line. The inequalities only give the general information for the existence of sliding mode, but not the information on the selection of the sliding coefficients [34]. The Ackerman formula [35] for designing static controller has been used for deriving sliding coefficients. However, in this paper, the selection of the sliding coefficient is formulated as an optimization problem solved with PSO.

In this paper, maximizing the power output for higher solar energy harvesting means minimizing the deviation of the output power (through the buck coverer) from the maximum power point (MPP) of the solar PV system. This involves substantial effort by the controller in the real time tracking of the MPP. Pertaining to the SM process, this would require obtaining the optimal state trajectory. Selection of the optimal sliding coefficient is a very important aspect of this approach. There has to be optimal values of the sliding coefficients with the range of values that comply with the SM hitting, existence, and stability conditions. The sliding coefficients selection optimization problem has to be formulated to satisfy the hitting, existence, and stability conditions for SM control.

3.1. The sliding coefficient selection optimization problem

The objective of the problem formulation is to select the SM sliding coefficients such that the resulting instantaneous state trajectory, commanded by the consequent switching action u, minimizes the output power deviation of the converter from the MPP of the PV system. The power deviation of MPP can be expressed in (20).

$$DEV_{mpp} = output\ power - I_{MPP} \times V_{MPP} \tag{20}$$

Where I_{MPP} is current at MPP and V_{MPP} is voltage at MPP. The quantity $I_{MPP} \times V_{MPP}$ is equivalent to the maximum power point. The optimization problem in (21) can be stated in (21).

$$min\ DEV_{mpp} = output\ power - I_{MPP} \times V_{MPP} \quad (21)$$

Subject to the satisfaction are: i) The SM heating condition; ii) the SM existence condition; and iii) the SM stability condition.

3.2. PSO algorithm for solving the problem

Based on the PSO algorithm, the solution of the optimization problem involves finding the best particles /positions (i.e. sliding coefficients) that realizes the objective function ($min\ DEV_{mpp}$) while satisfying the constraints. Particles, which are considered to fly through the solution space by following their own experience and current best position (P_{best}) are the potential solution to the optimization problem. In the present problem, the solution space is constrained by the SM process hitting, existence and stability conditions. The positions of the particles converge to the desired optimal sliding coefficients. In this paper it should be noted that ‘particle’ and ‘position’ are interchangeable. Similarly, ‘swarm’ and ‘population’ and their usage are interchangeable. The PSO algorithm for solving the sliding coefficients selection optimization problem is presented in Figure 3 and Figure 4 shows the Simulink model of the sliding mode MPPT solar power system.

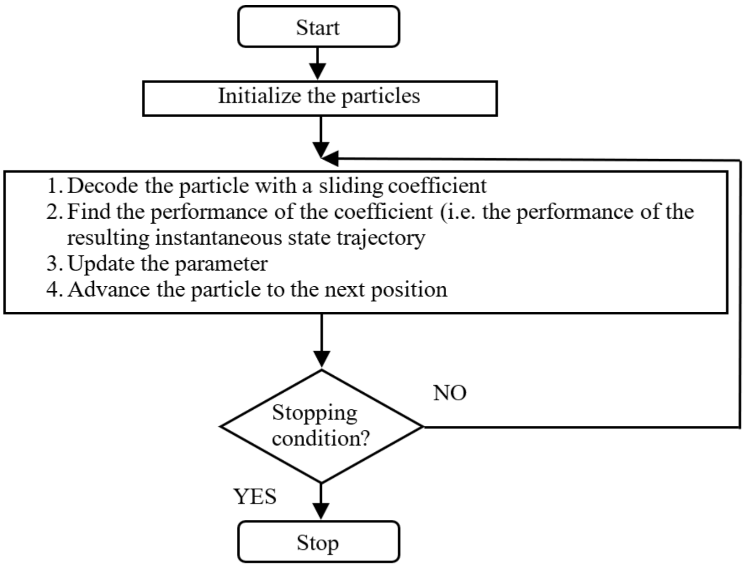

Figure 3. PSO flow chart for solving the sliding coefficient selection problem

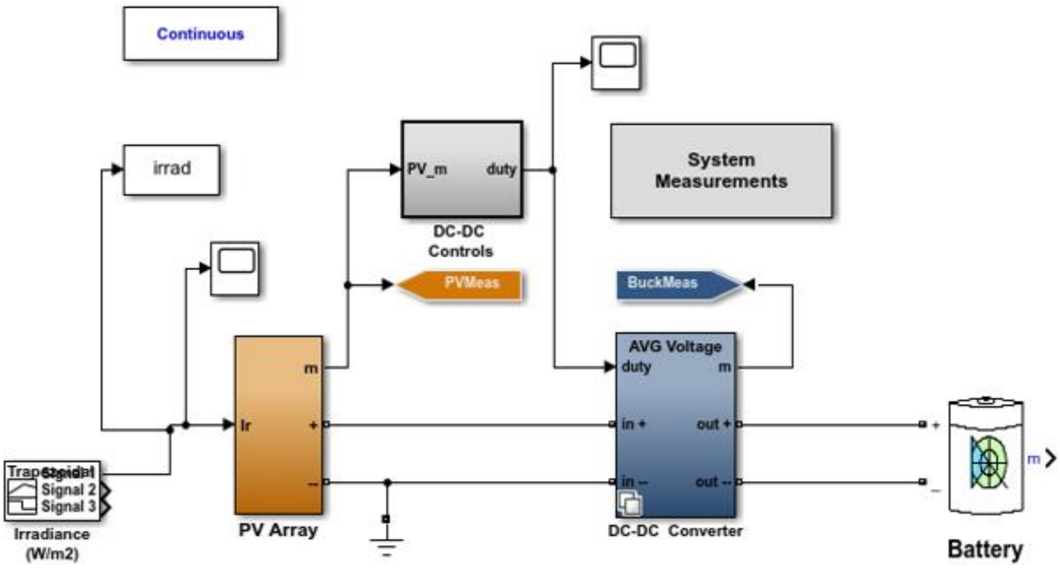

Figure 4. Simulink model of the sliding mode MPPT solar power system

4. SIMULATION RESULTS

This section summarizes the performance results of simulated MPP tracking using the PSO based SM controller and the conventional SM controller. The algorithms are implemented in MATLAB 2019. Base data for simulating varying solar irradiance was provided by National Centre for Energy Research and Development, University of Nigeria Nsukka. Model for simulating the PV generator is based on the Ideal single diode model (ISDM). The short-circuit current and open-circuit voltage are 8.34 A and 44.17 V respectively. The MPP is at 37.0 V and 7.79 A under standard testing condition. The peak power is 288.3 W. The PSO parameters are listed in Table 1.

From the results obtained the MPP tracking performances of the PSO based SM controller and the conventional SM controller were compared. Figure 5 shows the plot of simulated actual PV array's current and tracked currents at MPP. Figure 6 shows the plot of actual PV array's voltage and the algorithms' tracked voltages at MPP. Figure 7 shows the variation of actual MPP of the solar array and the output MPP as tracked by the PSO based SM controller and the conventional SM controller. The output current and voltage of the converter commanded with the PSO Based SM controller varies closer to the actual solar array current and voltage at MPP respectively than those commanded by the conventional SM controller. Figure 6 it can be observed that the PSO based SM controller more accurately tracks the actual maximum power points and rises to the MPP orders of magnitude more rapidly than that tracked by the conventional SM controller.

Table 1. Settings of the PSO parameters

Parameter	Symbol	Value
Number of particles	I	100
Number of iterations	T	1000
Number of Neighbors	K	5
Inertia weight	w	Linearly decreased from 0.9 to 0.1
Personal best position acceleration constant	c_p	2
Global best position acceleration constant	c_g	2
Constant of $Ibest$ social term	c_l	1.5
Constant of $nbest$ social term	c_n	1.5

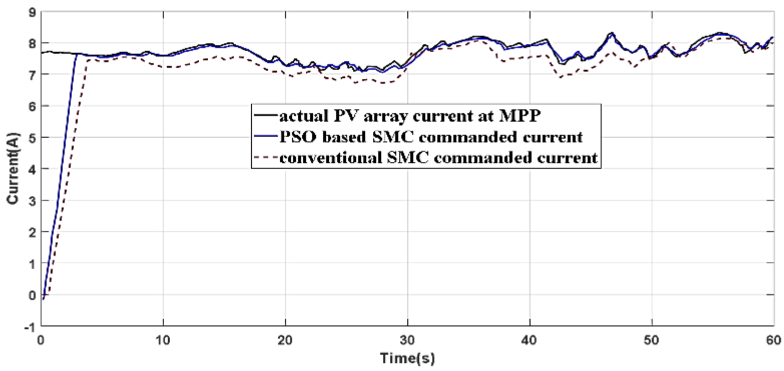

Figure 5. Comparison of output current at load side for MPPT control using the PSO based SMC and the conventional SMC

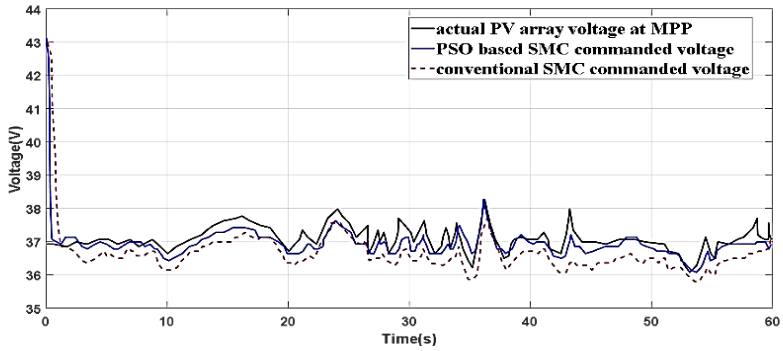

Figure 6. Comparison of output voltage at load side for MPPT control using the PSO based SMC and the conventional SMC

The MPPT tracking efficiency of the controllers are obtained using the (26):

$$\eta_{MPPT} = \sum_{1}^{n} \frac{P_{real,i}}{P_{thmax,i}} \tag{26}$$

Where P_{real} represents power out of the system (actual power receive by the load). The P_{thmax} is the theoretical maximum power available at the solar PV module and n is the number of samples. Table 2 lists the actual PV array's MPPs (P_{thmax}), the MPPPs as tracked (P_{real}) by the PSO based SM controller and the conventional SM controllers taken at intervals of 5 seconds.

The actual simulated maximum power of PV array, the MPP tracked by the PSO based SM controller and by the conventional controller taken at interval of 5 seconds. MPPT tracking efficiencies obtained for the PSO based SMC and the conventional SMC are 99.65% and 96.79% respectively. The PSO based SMC achieved a better tracking efficiency than the conventional SMC.

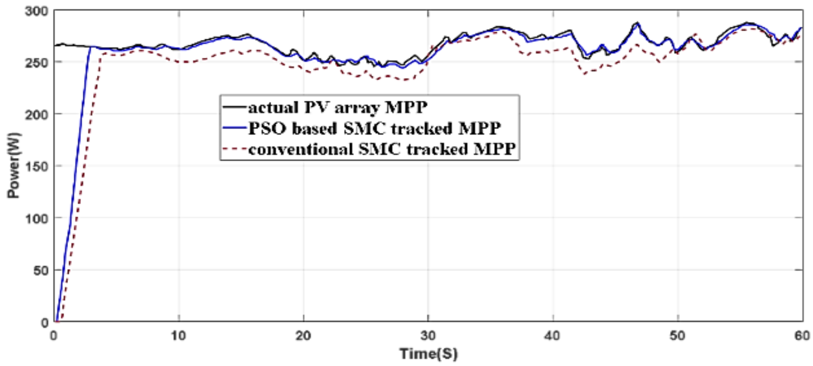

Figure 7. Comparison of output power for MPPT control using the PSO based SMC and the conventional SMC

Table 2. Comparison of PSO based SM controller tracked MPP(W) with conventional SM controller tracked MPP(W)

Time (sec)	Actual MPP (W)	PSO based SM controller tracked MPP (W)	Conventional SM controller tracked MPP (W)
5	263.0878	260.7367	256.5047
10	262.1473	262.6176	250.8621
15	274.3730	271.5517	257.9154
20	251.3323	251.8025	242.3981
25	254.1536	254.6238	238.6364
30	256.5047	251.3323	256.0345
35	280.9561	280.0157	276.2539
40	273.4326	274.3730	260.7367
45	261.2069	259.3260	248.5110
50	259.7962	261.2069	258.8558
55	284.7179	284.2476	279.5455
60	283.7774	282.3668	276.2539

5. CONCLUSION

In order for the PV system to operate around the reference MPV using the boost converter duty cycle, the SMC controller is built to allow the PV output voltage to track the reference voltage. In order to identify the ideal SMC parameter values, the PSO evolutionary algorithm is applied, ensuring the right system trajectory for changing atmospheric circumstances. In comparison to previous controllers, the simulation results showed that the suggested PSO-SMC exhibits the greatest performance in terms of transition responsiveness, tracking error, and control signal smoothness. The selection of the sliding coefficients for the design the SM controllers can be improved using optimal search algorithms. The results obtained in this paper indicates that using PSO to design the sliding surface produces SMC MPPT algorithm that achieves better performance than the conventional SMC algorithm.

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