Robust maximum power point tracking control for photovoltaic system based on second order sliding-mode

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ABSTRACT

This paper proposes a control approach of a maximum power point of a photovoltaic (PV) system using the second order sliding mode approach. The main objective of the proposed paper is to track the maximum power point (MPP) using super twisting algorithm (STA) with a one-loop control method and augment efficiency of the output power system. The structure of a proposed approach is simple and robust aging the atmospheric changes. Such control approach solution has several advantages such as simple implementation, robustness; reduce the chattering phenomenon and good dynamic response compared to traditional first-order sliding mode control algorithm. The controller circuit adapts the duty cycle of the switch electronic device of the DC/DC converter to search maximum power point tracking as a function of evolution of the power input. The effectiveness and feasibility of the proposed control are verified by simulation in MATLAB/Simulink environment and dSPACE-based hardware in loop platform.

Keywords:
dDSpace controller board
Maximum power point
Shell Solar S75 PV
Sliding mode control
Super twisting algorithm

1. INTRODUCTION

Solar energy represents a viable energy alternative for the production of electricity since the latter is a renewable source, both clean, unlimited and with a very low level of risk [1-3]. However, a major challenge in using an energy generated by photovoltaic systems is to undertake its nonlinear output characteristics, which depend of solar insolation and temperature module. An important in the operation of a PV generator is to reach the maximum output power by means of continuously correcting the PV array operating point for the given conditions. The main objective of maximum power point tracking (MPPT) method is to automatically obtain an optimal MPP operation under real outdoor conditions.

Several MPPT techniques have been developed in literature. Some of the popular schemes are the Open-circuit voltage method [4], incremental conductance methods [5, 6] and perturb and observer (P&O) methods [7]. In the open circuit voltage technique, in order to calculate $V_{OC}$, power inverter should be turned off for a few seconds. Thus, at each calculation, some power is lost. Another drawback of this technique is that it cannot track MPP at the effects of the irradiation changes. The P&O is most widely due to its simplicity and easily implemented. However, P&O have major disadvantage because he does not consider the effects when the atmospheric conditions change rapidly [8, 9]. Incremental conductance can perform MPPT faster under different atmospheric conditions with high accuracy but it increase system complexity.

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There are also other algorithms such as the artificial neutral network technique (ANN) [10], particle swarm optimization (PSO) [11], fuzzy logic approach [12] and adaptive neuron-fuzzy technique [13]. The algorithms should have a high performance to MPP track. However, their implementations are expensive and complex [14]. In that sense, robust Sliding Mode Control is an interesting solution for non-linear control derived from variable structure control (VSC) system theory and developed by UTKIN [15]. Such controller has many advantages for example, simple implementation, well dynamic response and good robustness.

VSC technique for PV application was proposed and evaluated by numerical study in [16]. Further study was also suggested in [17-19], however, these approaches required current or a voltage reference for control law synthesis and can lead to a lack of robustness to operation conditions. In [20] there is no necessity to have a reference value since the sliding surface guarantees the MPP when it is equal to zero. But the chattering phenomenon, originated by the interaction between parasite dynamic and finite-frequency switching control is the main disadvantages of this techniques of control [21, 22]. To minimize chattering phenomena some methods were proposed [23-25]. To preserve the main advantages of the sliding mode technique and to reduce the chattering phenomenon, a novel class of SMC algorithm, called second-order SMC algorithm (2-SMC) has been proposed in [26, 27].

In Sahraoui et al. [28], a 2-SMC was applied with a two-loop control approach. A simulation study by Yatimi et al., [29] presents a robust sliding mode method for a photovoltaic energy storage system. Another method to track the MPP given in Mojallizadeh et al., [30], the proposed scheme is based on the second-order fuzzy sliding mode control law of photovoltaic power generation systems with a two-loop control. Moreover, in Kckaou et al., [31] offer a second-order sliding MPPT control for photovoltaic application. The main objective of this work is the use one loop technique of 2-SMC based on super twisting algorithm to extract MPP, reduce the chattering phenomenon and real-time implementation study under different operating scenarios. The control circuit use an algorithm to adapt the duty cycle of the switch control of the DC-DC converter to search MPP tracking as a function of evolution of the power input. This paper consists of four sections, including the introduction. Section 2 materials and methods, and section 3 results and discussion. Finally, the conclusions of the study are given in section 4.

2. MATERIALS AND METHODS
2.1. Photovoltaic systems
2.1.1. Mathematical modelling and simulation

The physical behaviour of the panel has conventionally been studied by representing it as an equivalent electrical circuit composed of linear and non-linear components. Solar cell (SPV) is the elementary component which converts the energy of light directly into electricity by the PV effect. PV arrays are built up with combined series/parallel combinations of SPV [32, 33]. Each cell is typically a p-n junction. There are various circuit schemes for a photovoltaic cell in literature. A single diode model is considered as the equivalent photovoltaic cell in the present paper [33]. The basic model for a photovoltaic cell is show in Figure 1.

![Figure 1. Simplified equivalent circuit PV model](image)

The one diode equivalent circuit determines the I-V characteristic of the cell is described by the following (1):

\[ I = I_{ph} - I_0 \left( e^{\left(\frac{V+I_{RS}}{V_T}\right)} - 1 \right) - \frac{V+I_{RS}}{R_{sh}} \]

where \( I \) is the cell output current (A), \( V \) is the cell output voltage (V), \( I_{ph} \) is the photocurrent, function of the irradiation level (G) and junction temperature, \( I_0 \) is the reverse saturation current of diode, \( V_T = aKT/q \) is the thermal voltage, \( q \) is the electron charge (1.602×10^-19 C), \( K \) is the Boltzmann constant (1.38×10^-23 J/K), \( a \) is...
the ideal factor, $T_c$ is the temperature of the cell, $R_s$ and $R_{sh}$ the serial and parallel resistances respectively and $I_d$, called diode (D) current or dark current. The photocurrent $I_{ph}$ can be assessed with the (2):

$$I_{ph} = I_{STC} \frac{G}{G_{STC}} \left[ 1 + \alpha (T_c - T_{c,STC}) \right]$$

where $I_{STC}$ is the short circuit current at standard test condition (STC), while $G_{STC}$ and $T_{c,STC}$ are the irradiation and temperature of the PV cell at STC, respectively; $\alpha$ is the current temperature coefficient.

With regard to the reverse saturation current $I_0$ parameter, its value changes with cell temperature at STC conditions and can be found by using the following (3).

$$I_0 = I_{rs} \left( \frac{T_c}{T_{c,STC}} \right) ^3 e^{\frac{qE_g}{kT_c} \left( \frac{1}{T_c} - \frac{1}{T_{c,STC}} \right)}$$

where $I_{rs}$ is the reverse saturation current at STC conditions, $E_g$ is the band-gap energy of the material. In this work for $R_s$ and $R_{sh}$ the same relations in [34] are used as (4) and (5).

$$R_{sh} = R_{sh,STC} \frac{G}{G_{STC}}$$

$$R_s = R_{s,STC}$$

where $R_{s,STC}$ and $R_{sh,STC}$ are the serial resistance and parallel resistance at STC conditions, respectively.

In (1) is valid for a solar cell. For the exact application of this equation for PV module, the term of $(V + R_s I)$ is replaced by $(V + R_s I N_s)$. To determine the five parameters exist in (1), which are: $I_{ph}$, $R_s$, $R_{sh}$, $I_0$ and $\alpha$, you can see [35, 36]. Typically $N_s$ cells are connected in series to get the requisite voltage of PV module. All the cells are forced to carry the same current called panel current in series panel. In this work, actual module was utilised, Shell Solar S75. The electrical parameters of the module under STC form manufacturer are listed in Table 1.

| Silicon type          | Shell solar S75 |
|-----------------------|-----------------|
| Open circuit voltage  | 21.6 V          |
| Short-circuit current | 4.7 A           |
| Maximal voltage       | 17.6 V          |
| Maximal current       | 4.26 A          |
| Maximal power         | 75 W            |
| Number of cells       | 36              |

Figure 2 shows the simulated and experimental results of the module under different irradiation and temperature levels. The current-voltage (I-V) and power-voltage (P-V) characteristics are shown in Figure 2. Figure 3 revealed the simulation structure of the closed loop system for MATLAB and Simulink, which includes the electrical schema of a one diode model of the PV panel. More details can be found in [37].
2.1.2. Dynamic model of DC/DC boost converter

In order to force the PV panel functions at the MPPT, we present the principle of the DC-DC boost converter. This type of converter uses inductors and capacitors to control the energy flow from the PV module to the load by continuously opening and closing a switch (K) \([38]\). The switch is generally an electronic device (MOSFET or IGBT transistor). It is driven by a pulse width modulation (PWM) signal with a fixed frequency and an adjustable duty cycle \(D (0<D<1)\). Figure 4 shows a DC-DC boost converter. The relation between the output voltage and input voltage in DC-DC boost converter is given by (6):

\[
V_0 = \frac{1}{1-D} V_{pv}
\]

(6)

the dynamic of the boost converter is given by:

\[
\begin{align*}
C_1\frac{dV_{pv}}{dt} &= I_{pv} - I_L \\
\frac{dI_L}{dt} &= V_{pv} - (1-D)V_0 \\
C_2\frac{dV_0}{dt} &= -I_0 + (1-D)I_L
\end{align*}
\]

(7)

where \(V_{pv}\) and \(I_{pv}\) are the voltage and current of the PV module, \(I_L\): the inductor current of the DC-DC converter. \(V_0\): the DC-DC converter output voltage, \(D\): the duty cycle, \(L\): the filter inductor, \(C_1\) and \(C_2\): the filter capacitor, \(R\): the nominal resistance of load.

By combining the different equations describing the system \([29]\), global dynamic model can be written as follows:

\[
\begin{align*}
1 &= I_{ph} - I_0 \left[ e^{\frac{(V_{pv}+V_{ns}R_s)}{V_{ns}R_{sh}}} - 1 \right] - \frac{V_{pv}+V_{ns}R_s}{N_p R_{sh}} \\
\frac{dV_{pv}}{dt} &= \frac{I_{pv}}{C_1} - \frac{I_L}{C_1} \\
\frac{dI_L}{dt} &= \frac{V_{pv} - (1-D)V_0}{L} \\
\frac{dV_0}{dt} &= \frac{I_0}{C_2} + \left(\frac{1-D}{C_2}\right)I_L
\end{align*}
\]

(8)

In (8) can be written in compact form of the nonlinear time invariant system:

\[
\begin{align*}
X_1 &= \frac{1}{C_1}V_{pv} - \frac{1}{C_1}X_2 \\
X_2 &= \frac{1}{L}X_1 - \frac{u}{L}X_3 \\
X_3 &= -\frac{1}{RC_2}X_3 + \frac{u}{C_2}X_2
\end{align*}
\]

(9)

where \(X_1 = V_{pv}; X_2 = I_L; X_3 = V_0; u = (1-D); I_0 = V_0/R;\)

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2.2. Second order sliding mode approach

As the supplied by the photovoltaic energy depends on outdoor conditions, an important account in the design of efficient PV systems is to extract MPP correctly. The purpose of MPPT is to move the output power operating close to the MPP under varying outdoor conditions. The 2-SMC is established for the systems with relative degree two (\(r=2\)) and does not suffer from chattering while maintaining the robustness of the approach. There are several algorithms to realize 2-SMC in literature. For example, sub-optimal algorithm, the terminal sliding mode algorithm, the twisting algorithm, the super-twisting algorithm. Hence, the STA algorithm is currently preferable over the classical sliding mode control.

2.2.1. Short review of 2-SMC

The SMC consists of two phases: first, we determine a sliding surface \(S(X)\) upon which the control objectives are realized. Next, we derive a control law in order to bring the state trajectory to this output and maintain it there at all time [39]. In the situation the difficult is to generate a 2-SM on an appropriately chosen sliding surface and, thus, to constrain the trajectories system to evolve in finite time on \(S = \{X; S = \dot{S} = 0\}\). However, the increasing information demand in terms of the first derivative of the sliding variable \(S\). Consider a system whose dynamics is given by:

\[
\dot{X} = f(X,t) + g(X,t)u
\]

\[
y = g(X,t)
\]

(10)

where: \(X \in \mathbb{R}^n\) is the system state variable, \(u \in \mathbb{R}\) is the control, \(f,g\) are sufficiently smooth vector fields. \(S = S(X,t) \in \mathbb{R}\) is the output function, called sliding variable. By differentiating \(S\) with respect to time, \(t\), we have:

\[
\dot{S} = \varphi_A(t,S) + \varphi(t,S)\dot{u}
\]

(11)

The control \(u\) is bounded function \(|u| \leq U_{\text{max}}\). The dynamics in (11) are assumed to satisfy the following bounding conditions [26]:

\[
0 < k_{\text{m}} |\varphi(t,S)| \leq K_{\text{M}}
\]

\[
|\varphi(t,X)| \leq \beta_{\text{0st}}
\]

(12)

The set \(\{t,X,u; |S(t,X)| < S_0\}\) is the linear region, where \(k_{\text{m}},K_{\text{M}}\) and \(\beta_{\text{0st}}\) are some positive constants. The algorithm includes two continuous terms that, again, do not depend upon the first time derivative of sliding variable. The algorithm can be defined by the following control law:

\[
u_{st} = u_1 + u_2
\]

(13)

where

\[
\begin{cases}
u_1 = -\alpha_1 \text{sign}(\dot{S}) \\
u_2 = \alpha_2 |S|^{\rho} \text{sign}(\dot{S})
\end{cases}
\]

(14)

with: \(\alpha_1, \alpha_2\) and \(\rho\) verifying the following inequality [27] and [40]:

\[
\frac{1}{\alpha_1} \geq \frac{1}{\alpha_2} \geq \frac{1}{\beta_{\text{0st}}}
\]
\[
\begin{align*}
\alpha_1 &= \frac{\beta_{\text{sat}}}{K_m} \\
\alpha_2 &= \frac{4\beta_{\text{sat}}K_m(\alpha_1+\beta_{\text{sat}})}{K_{\text{sat}}K_m(\alpha_1-\beta_{\text{sat}})} \\
0 &< \rho \leq 0
\end{align*}
\]

The choice \( \rho = 0.5 \) ensures that he maximal possible for 2-SMC assures the finite time convergence.

### 2.2.2. Robust 2-SMC MPPT control approach

In this work the STA has been designed to search MPP. The super twisting algorithm is established for the system with relative degree one so as to reduce the chattering [31]. To make sure that the system states will hit the sliding surface and provides the MPP output, we choose the sliding surface as given in [19]. The state (9) can be expressed by:

\[
X = f(X,t)+g(X,t)u \\
S(X,t) = \frac{\partial \rho_{\text{pv}}}{\partial \text{pv}} = I_{\text{pv}} + V_{\text{pv}} \frac{\partial I_{\text{pv}}}{\partial V_{\text{pv}}} = 0
\]

where \( X = [I_{\text{pv}} \quad V_0]^T, u = [0 \quad 1] \). The sliding mode surface \( S(t) \) is defined as:

\[
S(X,t) = \frac{\partial \rho_{\text{pv}}}{\partial \text{pv}} = I_{\text{pv}} + V_{\text{pv}} \frac{\partial I_{\text{pv}}}{\partial V_{\text{pv}}} = 0
\]

If we differentiate the sliding surface \( S \), we can write [29]:

\[
\dot{S} = \varphi_A(t,S,\dot{S}) + \varphi(t,S,\dot{S})\dot{u}
\]

with

\[
\varphi_A(t,S,\dot{S}) = \left( \frac{\partial^2 \rho_{\text{pv}}}{\partial V_{\text{pv}}^2} \right) \frac{\partial V_{\text{pv}}}{\partial t} \left( \frac{\partial V_{\text{pv}}}{\partial t} \right) + \frac{1}{c_1} \left( \frac{\partial^2 \rho_{\text{pv}}}{\partial V_{\text{pv}}^2} \right) \left( \frac{\partial V_{\text{pv}}}{\partial t} \right) - \frac{V_{\text{pv}}}{L}
\]

\[
\varphi(t,S,\dot{S}) = \frac{1}{c_1} \left( \frac{\partial^2 \rho_{\text{pv}}}{\partial V_{\text{pv}}^2} \right) \frac{V_0}{L}
\]

where

\[
\begin{align*}
\frac{\partial^2 \rho_{\text{pv}}}{\partial V_{\text{pv}}^2} &= \frac{\partial I_{\text{pv}}}{\partial V_{\text{pv}}^2} + \frac{\partial V_{\text{pv}}}{\partial t} \frac{\partial^2 I_{\text{pv}}}{\partial V_{\text{pv}}^2} \\
\frac{\partial^3 \rho_{\text{pv}}}{\partial V_{\text{pv}}^3} &= \frac{\partial^2 I_{\text{pv}}}{\partial V_{\text{pv}}^2} + \frac{\partial V_{\text{pv}}}{\partial t} \frac{\partial^3 I_{\text{pv}}}{\partial V_{\text{pv}}^3}
\end{align*}
\]

The control of the boost converter is a bounded function (0<\( u < 1 \)). We assume that the (18) satisfy condition in (15), the control law guarantees the finite time convergence. The proof of the control law algorithm approach is presented in the appendix. We can consider the applied control law and \( D \) can be deduced from the equation \( u=1-D \). it is guaranteed that the system state will hit the surface and produce maximum power output persistently.

### 3. RESULTS AND DISCUSSION

The structure of the closed loop system for MATLAB and Simulink, is shown in Figure 5, which includes the electrical circuit of the photovoltaic module Shell Solar S75, whose characteristics are shown in Table 1, the DC-DC converter BOOST work with \( L=130\mu\text{H}, C_1=1000\mu\text{F} \) and \( C_2=500\mu\text{F} \), load \( R=20\Omega \) and the MPPT algorithm. The switching frequency of the boost converter is set to 25 KHz. The controller parameters are set to \( \alpha_1=0.27 \) and \( \alpha_2=0.05 \). The proposed MPPT control is evaluated from three cases including fixed irradiation, varying irradiation and temperature. Furthermore, for the sake of comparison, responses obtained with 2-SMC based on super twisting algorithm (STA) are compared with ones resulting from the 1-SMC (fixed irradiation).
3.1. Standard test conditions: T=25°C and G=1000 W/m²

Figure 6 (a) displays the waveforms of $P_{pv}$, $V_{pv}$, $V_{0}$, $I_{pv}$ and D with the 1-SMC as an MPPT Controller. Figure 7 (a) and displays the waveforms of $P_{pv}$, $V_{pv}$, $V_{0}$, $I_{pv}$ and D with the 2-SMC based on STA as an MPPT controller, so that the MPP is located at a power of 75.02 W. It is easily from the below results seen that the system reaches that PV module power and shows a fast response and a good tracking performance. It only takes milliseconds to track MPP. When the MPP is reached, the sliding surface converges to zero Figure 7 (b).
The simulation characteristic curves results (2-SMC) of the photovoltaic system are presented in Figure 8. Figure 9 shows the comparison between PV output power, duty cycle of 2-SMC and 1-SMC as an MPPT controllers tracker. The 2-SMC presents less oscillation than the 1-SMC and which imply good conversion efficiency. All these results prove the effectiveness of our STA control.

3.2. Varying solar irradiation test

Figure 10 (a) shows the tracking results with step irradiance input from 500 W/m² to 800 W/m² at 0.4s and 800 W/m² to 1000 W/m² at 0.6s, while the temperature is constant equal to T=25°C and load R=20Ω. The system reaches steady state of irradiance levels within milliseconds and can track the desired behavior of the MPP rapidly Figure 10 (a) and with less oscillation which implies good conversion efficiency Figure 10 (b).

3.3. Varying temperature

Figure 11 shows the tracking results with step temperature input from 25°C to 50°C at 0.4s, while the irradiance is constant equal to 1000 W/m² and load R=20Ω. The controller reaches steady state of both temperature levels within small time transit response.

3.4. Experimental results

The basic structure of the laboratory setup (LSP-IE laboratory, University of Batna 2) is illustrated in Figure 12. The Resistance is used as a load. The emulator connected with a boost converter has been used instead of the module. The dSPACE DS1104 PPC is plugged in the host PC. The sensors used for the currents and voltages measure are respectively LA-25NP and LV-25P. The MPPT control law has been implemented in a dSPACE DS1104 R&D controller board. Then the PWM unit directly generates a 25 KHz PWM signal to control IGBT switch of the boost converter. The experimental characteristics of the photovoltaic emulator are shown in Figure 13.
The performance and robustness of the MPPT algorithm is evaluated by two experiments:
- Under fixed values of irradiation (G=1000 W/m²) and Temperature (T=25°C).
- Under varying irradiation from 500 W/m² to 1000 W/m² and T=25°C.
The results as shown in Figure 14 demonstrate that the 2-SMC method has good dynamic response and can track the desired behaviour of the MPP power (100 W) well. The 2-SMC is proving robustness against irradiation variation shown in Figure 15.

Figure 14. Experimental results of 2-SMC under fixe value of irradiation and temperature

Figure 15. Experimental results of 2-SMC under varying value of irradiation and fixe temperature value

4. CONCLUSION

In this work a robust MPPT control is proposed for the PV application. The proposed controller is capable to track the MPP under different operating conditions. This approach guarantees high dynamic system performances and higher efficiency compared to other algorithms. The robustness against change in irradiation of the proposed method is improved via simulation under MATLAB/Simulink. Also the proposed algorithm offers a solution to eliminate the chattering phenomenon. This approach is the foundation of a practical implementation follow-up this research work. The effectiveness and the feasibility of the improved 2-SMC was verified by experiments

APPENDIX

Proof. In order to demonstrate the stable convergence property of the proposed approach [41]:

$$S(X, t) = \frac{\partial P_{pv}}{\partial V_{pv}}$$  \hspace{1cm} (A.1)

If $S(X, t)$ is made equal to zero, then the maximal power is taken. The controller steer the derivative $S$ to zero, by action on the duty cycle $u$. We can write:

$$S(X, t) = \frac{\partial P_{pv}}{\partial V_{pv}} = I_{pv} + V_{pv} \frac{\partial I_{pv}}{\partial V_{pv}} = 0$$  \hspace{1cm} (A.2)
In view of (1) and $R_s$, $R_{sh}=\infty$, its dynamics is given by:

$$\dot{S} = -\frac{l_o}{V_{fc1}} e^{\frac{V_{pv}}{V_t}} \left(2 + \frac{V_{pv}}{V_t} \right) (I_{pv} - I_L)$$  \hfill (A.3)

The second derivative of $S$ is described by the following (A.4):

$$\ddot{S} = -\frac{l_o}{V_{fc1}} \left[ 1\frac{1}{V_{fc1}} \left(3 + \frac{V_{pv}}{V_t} \right) (I_{pv} - I_L)^2 + \left(2 + \frac{V_{pv}}{V_t} \right) \left(\frac{dI_{pv}}{dt} - \frac{1}{L} (V_{pv} - V_0) \right) \right]$$  \hfill (A.4)

As shown in (A.4) can be rewritten as follows:

$$\ddot{S} = \varphi_A(t, S, \dot{S}) + \varnothing(t, S, \dot{S}) u$$  \hfill (A.5)

where

$$\varphi_A(t, S, \dot{S}) = -\frac{l_o}{V_{fc1}} e^{\frac{V_{pv}}{V_t}} \left[ A \frac{1}{V_{fc1}} \left(3 + \frac{V_{pv}}{V_t} \right) (I_{pv} - I_L)^2 + \left(2 + \frac{V_{pv}}{V_t} \right) \left(\frac{dI_{pv}}{dt} - \frac{1}{L} (V_{pv} - V_0) \right) \right]$$  \hfill (A.6)

$$\varnothing(t, S, \dot{S}) = \frac{l_o}{V_{fc1}} \left(2 + \frac{V_{pv}}{V_t} \right) e^{\frac{V_{pv}}{V_t}}$$  \hfill (A.7)

As shown in (A.5) has the relative degree two with respect to the input $u$.

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