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Robust Sliding Mode MPPT control of a Photovoltaic System

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Abstract—**This paper proposes a robust sliding mode controller based MPPT (RSMC-MPPT) for maximum power point (MPP) of a stand-alone photovoltaic (PV) system. The design method provides good robustness proprieties face to the system uncertainties and the variations in environmental circumstances. First, the Perturb and Observe algorithm (PO) is used to find the reference voltage. Then a sliding mode controller is introduced to regulate the PV array voltage to the reference voltage. The process iterates the optimal voltage searching and the PV voltage tracking until the maximum power is reached. Finally, the performance of the RSMC-MPPT is verified through simulations.**

I. INTRODUCTION

Over the past few decades, the world demand for energy has risen steadily, forcing the world communities to look for alternative sources. Photovoltaic (PV) is seen as the most promising solution for this demand. It has received much attention with many feasible applications [1], [2], [3]. However, the PV system is popularly known to suffer from low-energy harvesting due to the change of environment conditions and load impedances. In general, there is a unique point on the I-V or P-V characteristic, called maximum power point (MPP), at which the entire PV system (array, converter, etc) operates with maximum efficiency and produces its maximum output power. Therefore maximum power point tracking (MPPT) tools are needed to maintain the PV arrays operating point at its MPP. Numerous MPPT methods have been reported in the literature; such as constant voltage, Perturb and Observe (P&O), incremental conductance, fuzzy logic, and artificial neural network methods. These techniques vary between them in many aspects, including simplicity, convergence speed, hardware implementation, sensors required, cost range of effectiveness and need for parametrization ([4], [5], [6], [7], [8]). Currently, the conventional method P&O is the most extensively used in commercial products. Its simple control structure and ease of implementation have made it as the popular choice.

To obtain easy implementation and assured stability, maximum power voltage (MPV) based approaches are developed using a two-loop MPPT control scheme [9], [10], [11]. In detail, the first loop is to determine the MPV reference of the PV array, and the second loop is to regulate the PV array voltage to the reference voltage. The procedure repeats the MPV reference searching and the PV voltage tracking until the maximum power is reached. The advantage is that some traditional MPPT algorithms, for example, incremental conductance method, perturb and observe method, etc., can be realized with guaranteed convergence stability. However, the tracking performance is highly dependent to the performance of the tracking controller in the second loop. The existing disturbances and uncertainties will also affect the control results. We can see that most of MPV based approaches renders to power chattering around the MPP. Or a good MPPT strategy should be able to track the true maximum power operating point accurately under all circumstances and overcome all nonlinearities and system uncertainties in the characteristic I-V curves. There are, so, a lot of space to be improved on MPV based MPPT.

In the other hand, the sliding mode (SM) controller ([12]) is a type of nonlinear controller which was introduced for controlling variable structure systems (VSS). Its major advantages are guaranteed stability and robustness against parameter, line, and load uncertainties. Moreover, being a controller that has a high degree of flexibility in its design choices, the SM controller is relatively easy to implement as compared to other types of nonlinear controllers. Such properties make it highly suitable for control applications in nonlinear systems. This explains the wide utilization of SM controllers in various industrial applications. Incidentally, characterized by switching, DC-DC converters are inherently variable structured. It is, therefore, appropriate to use SM controllers for the control of DC-DC converters [13], [14]. This seems more naturally so considering the excellent large-signal handling capability that the SM control can offer. Since the design of conventional pulse-width modulation (PWM) controllers in power electronics is small-signal based, the system being controlled operates optimally only for a specific condition and often fails to perform satisfactorily under large parameter or load variations (i.e. large-signal operating condition). By substituting the linear PWM controllers with SM (nonlinear) controllers in power converters, better regulation can be achieved for a wider operating range. This arouses a lot of interests in the use of SM controllers for DC-DC converters. Generally, the conventional SMC consists of two steps called sliding step and reaching step. Firstly, design of a sliding surface such that the system possesses the desired performance when it is restricted to the surface. Secondly, synthesise a control law which induces a sliding motion on the sliding surface in finite time. For a good survey on the SMC approach, we refer readers to the work of Pisano [15] and references therein.

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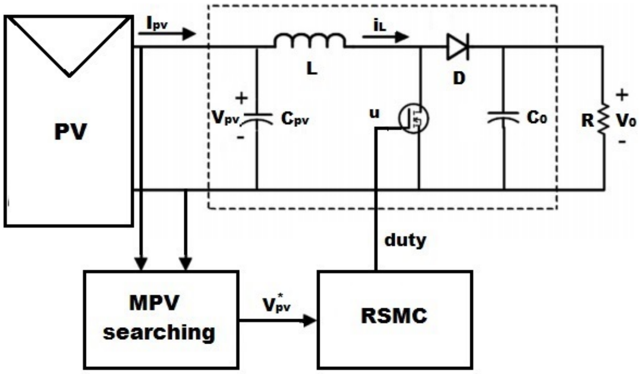

Fig. 1. Solar power generating system.

Motivated by the above analysis, a SMC-based MPPT scheme for standalone PV power generation systems is developed, in this paper, via the MPV based design. In the first loop, the MPV reference is obtained from the P&O algorithm. By taking a DC/DC boost converter as the power control circuit, RTMSC is introduced to drive the system to the MPV reference in the second loop. Meanwhile, the robustness against disturbance and system parameter uncertainties of the DC/DC boost converter is guaranteed.

The paper is organized in the following way: Section 2 describes the electric characteristics of PV power generation system. MPP searching via P&O and power tracking via RSMC are addressed in Sections 3. Numerical simulations are given in Sections 4. Finally, Section 5 concludes the paper.

II. SYSTEM DESCRIPTION

Fig. 1 describes a topology of a stand-alone PV system. It consists of a PV panel, a dc/dc boost converter, a load, and a control circuit that generates PWM signal that goes to the boost converter for MPPT operation.

II.1 *PV Pannel*

The electric description of a PV module is given in terms of output current I_{pv} and voltage V_{pv} [16]

$$I_{pv} = I_{ph} - I_s \left[exp\left(\frac{V_{pv} + R_s I_{pv}}{n_s V_t} \right) - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad (1)$$

where I_{ph} and I_s are the photocurrent and the saturation current, respectively. R_s, R_{sh}, V_t and n_s are the series resistance, the shunt resistance, the thermal voltage and number of series cells in the PV panel, respectively. Figs. 2 and 3 give the current-voltage (I-V) and power-voltage (P-V) characteristics of a PV module for different values of solar radiation G and temperature T, respectively.The output power of PV panel is always changing with weather conditions. Therefore, a MPPT control is required to extract its maximum power.

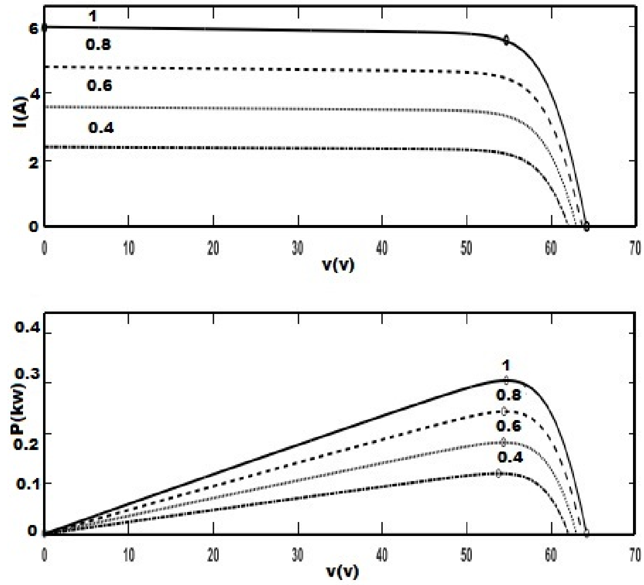

Fig. 2. Solar radiation (kw/m^2) influence on the IV and PV characteristics.

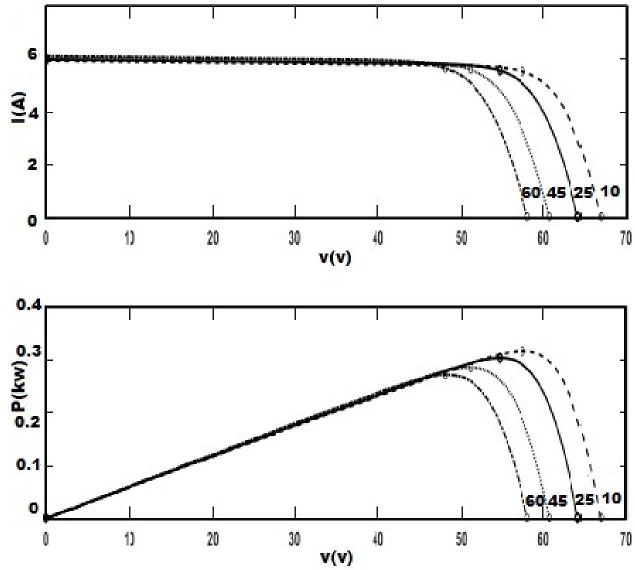

Fig. 3. Temperature ($^\circ c$) influence on the IV and PV characteristics.

II.2 *Boost converter*

By using the average method, the dynamic equations of the boost converter, with the PV array, is written as

$$\dot{i}_L = \frac{1}{L} V_{pv} - \frac{1}{L} V_0 (1-u) + \Delta(t) \quad (2)$$

$$\dot{V}_0 = \frac{1}{RC_0} V_0 + \frac{1}{C_0} i_L (1-u) \quad (3)$$

$$\dot{V}_{pv} = \frac{1}{C_{pv}} (i_{pv} - i_L) \quad (4)$$

where i_L denotes the current through the inductance L, V_0 is the output voltage, R is the resistive load, $u \in [0,1]$ denotes the duty cycle of the PWM control input and $\Delta(t)$ are the uncertain parts arising from measurement errors, system uncertainties, variations in V_{pv}, and load variations. Meanwhile, $\Delta(t)$ satisfies the following condition

$$\|\Delta(t)\| \leq \mu; \mu > 0 \tag{5}$$

III. ROBUST SLIDING MODE MPPT CONTROL

III.1 *MPV searching algorithm*

With a spurt in the use of renewable energy sources, PV power generation is being employed in many applications. However, every solar module holds a particular optimal operating point termed as maximum power operating point (MPOP) or peak operating point (POP) where solar module generates maximum possible power. This point is dependent on the sun radiations and cell temperature and varies with respect to these parameters (Figs. 2 and 3). It's obvious that both parameters do not remain constant during the whole day. Sometimes cloudy weather (or shadows) changes the conditions very abruptly and MPOP is also changed accordingly. In this way solar module offers variable source impedance in case if we keep load impedance constant. Now if the load impedance is not kept constant while the solar output voltage and output current values are assumed to be constant at a particular moment, again we need impedance matching. Similarly we need impedance matching in third case, when both source and load impedances are variable. This matching yields maximum possible power from solar modules and process of tracking this impedance matching point is called maximum power point tracking (MPPT). MPPT operates solar PV modules in a manner that allows the modules to produce all the power they are capable of generating. MPPT is now prevalent in grid-tied PV power systems and is becoming more famous in stand-alone systems. To extract the MPP, various techniques have been developed in the research literature. These techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, tracking performance and ease of implementation. The Perturb & Observe (P&O) algorithm [17], also known as the hill climbing method, is very popular and the most commonly used in practice because of its simplicity in algorithm and the ease of implementation. The most basic form of the P&O algorithm operates as follows. Considering the P-V curve and assuming the PV module is operating at a point which is away from the MPP, at the constant irradiance and the constant module temperature. In this algorithm the operating voltage of the PV module is perturbed by a small increment ΔV, and the resulting change of power, ΔP, is observed. If the ΔP is positive, then it is supposed that it has moved the operating point closer to the MPP. Thus, further voltage perturbations ΔV in the same direction should move the operating point toward the MPP. If the ΔP is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP. This iteration is continued until the algorithm finally reaches the MPP. Figure 5 shows the flowchart of this algorithm. The update law for V_{pv}^* is given by the following rules

$$\begin{cases} V_{pv}^*(k) = V_{pv}^*(k-1) + \Delta V & if \quad \Delta V \times \Delta P > 0 \\ V_{pv}^*(k) = V_{pv}^*(k-1) - \Delta V & if \quad \Delta V \times \Delta P < 0 \\ V_{pv}^*(k) = V_{pv}^*(k-1) & if \quad \Delta P = 0 \end{cases} \tag{6}$$

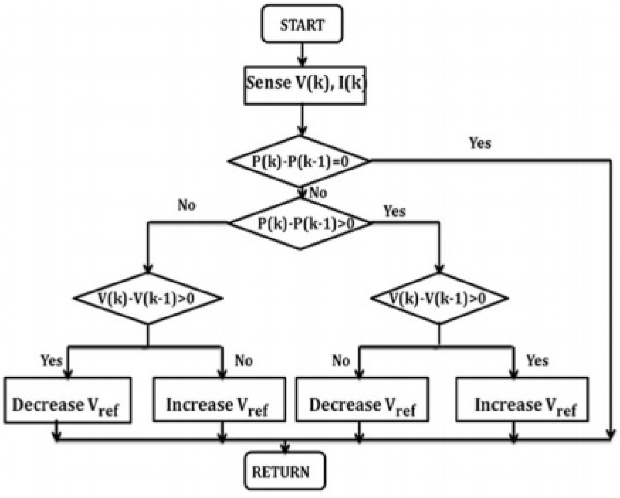

Fig. 4. Flowchart of the P&O algorithm.

III.2 *Robust sliding mode control*

To achieve the maximum power tracking, the sliding mode controller is introduced to make the PV voltage V_{pv} tracks the reference V_{pv}^* . Once V_{pv} always follows V_{pv}^*, the PV power system will move to the maximum power point along the P&O (hill climbing) adjusting. The SMC approach offers stability and robustness against parameters, input and load uncertainties, which are common in PV systems. Moreover, sliding-mode controllers are simpler to implement in comparison with other types of non-linear controllers. As a preliminary step to design procedure, define the voltage and current tracking errors, respectively as

$$e_1 = V_{pv} - V_{pv}^* \tag{7}$$

$$e_2 = i_L - i_L^* \tag{8}$$

such that the reference current is $i_L^* = I_{pv} - C_{pv}\dot{V}_{pv}^*$. Hence, the error dynamics are obtained

$$\dot{e}_1 = \frac{1}{C_{pv}}(I_{pv} - i_L) - V_{pv}^* = -\frac{e_2}{C_{pv}} \tag{9}$$

$$\dot{e}_2 = \frac{1}{L}V_{pv} - \frac{1}{L}V_0(1-u) + \Delta(t) - i_L^* \tag{10}$$

The control objectives is to :

- Design the sliding surface such that the tracking errors are null ($e_1 = 0$ and $e_2 = 0$).
- Synthesize the PWM control input $u(t)$ through a SM controller that robustly drives the errors (e_1 and e_2) toward the sliding manifold in finite time and maintains them on it thereafter.

The sliding function can be defined as follows

$$s(t) = e_2 - \lambda e_1 \tag{11}$$

with $\lambda > 0$.
If $s(t) = 0$ such that

$$e_2 = \lambda e_1 \tag{12}$$

the error (9) becomes

$$\dot{e}_1 = -\frac{\lambda}{C_{pv}} e_1 \tag{13}$$

which represents a stable dynamic and the convergence of e_1 to zero is then concluded. Hence, the convergence of the tracking error e_2 is also accomplished ($e_2 = \lambda e_1$). As a result, if the system is driven to the sliding surface $s(t) = 0$, the errors e_1 and e_2 will converge to zero. In other meaning, V_{pv} always follows the MPP voltage V_{pv}^*.

Theorem 1

Consider the photovoltaic power generation system described by the dynamical equations (2)-(4). For $\rho = \mu + \beta$ ($\beta > 0$), the robust sliding mode control

$$u(t) = -\frac{L}{V_0}\left[\frac{1}{L}(V_{pv} - V_0) + \frac{\lambda}{C_{pv}} e_2 - \dot{i}_L^* + \rho\, sign(s)\right] \tag{14}$$

ensures the maximum power point tracking in finite time.

Proof

Take the Lyapunov function

$$V(s) = \frac{1}{2} s^2 \tag{15}$$

Using the control law (14), the time derivative of $V(s)$, along the trajectory of (9)-(10), is given by

$$\begin{aligned} \dot{V}(s) &= s\dot{s} = s(\dot{e}_2 - \lambda \dot{e}_1) = s\left(\dot{e}_2 + \frac{\lambda}{C_{pv}} e_2\right) \\ &= \frac{1}{L}(V_{pv} - V_0) - \dot{i}_L^* + \frac{\lambda}{C_{pv}} e_2 + \Delta(t) + \frac{1}{L} V_0\, u \\ &= s(-\rho sign(s) + \Delta(t)) \qquad (16) \\ &\leq -\rho \|s\| + \mu \|s\| \leq -\beta \|s\| = -\sqrt{2}\,\beta \sqrt{V(s)} \end{aligned}$$

The reachability condition $s\dot{s} \leq 0$ is assured. Integrating both sides from 0 to $t > 0$, we have

$$\sqrt{V(s(t))} - \sqrt{V(s(0))} \leq -\sqrt{2}\beta t, \tag{17}$$

In fact, suppose that the system states cannot reach the sliding mode $s = 0$ within finite time, then from $\sqrt{V(s(t))} \leq \sqrt{V(s(0))} - \sqrt{2}\beta t, \sqrt{V(s(t))}$ becomes negative with t sufficiently large. This contradicts with $\sqrt{V(s(t))}$ nonnegative. In this way considering t_f as the time required to heat $s = 0$ and noting that $s(t = t_f) = 0$, one has

$$t_f \leq \frac{\|s(0)\|}{\sqrt{2}\beta}. \tag{18}$$

So, the proposed sliding mode control (14) brings the tracking errors e_1 and e_2 onto the switching manifold in finite time t_f and kept them, there, afterwards. This is the end of proof.

TABLE I
SPECIFICATIONS OF THE PV PANEL SUNPOWER SPR-305-WHT-U.

Parameter	Value
Maximum output power $P_{\max}$	$305W \pm 5\%$
Optimal current I_{mp}	$5.58A$
Open circuit voltage V_{oc}	$64.2V$
Short circuit current i_{scr}	$5.96A$
Ideality factor A	0.94497

IV. SIMULATION RESULTS

The general structure of the PV system, depicted in Fig. 1 , is constructed here with $C_{pv} = 2000\mu F$, $C_0 = 2000\mu F$, $L = 10mH$ and $R = 68\,\Omega$. The specifications of the adopted 305 W PV module are given in Table I. To verify the effectiveness of the proposed RSMC-MPPT, three cases are investigated here.

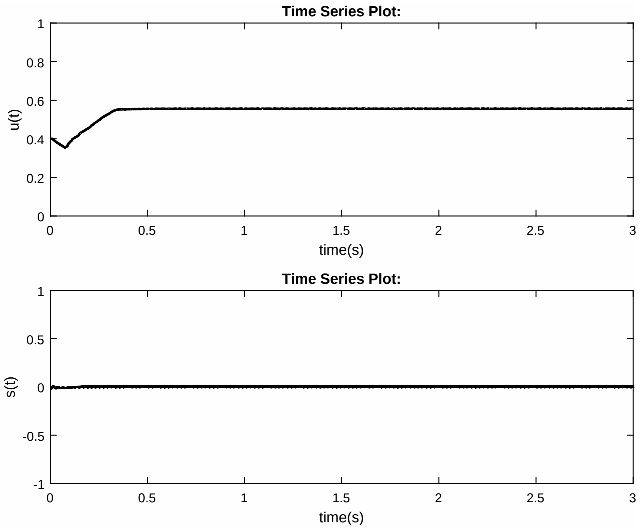

Fig. 5. MPPT control responses in case 1:$u(t)$ and $s(t)$.

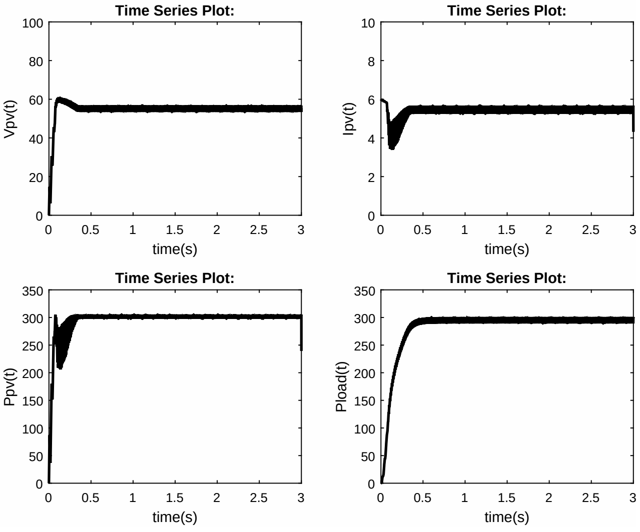

Fig. 6. MPPT control responses in case 1:V_{pv}, I_{pv}, P_{pv} and P_{load}.

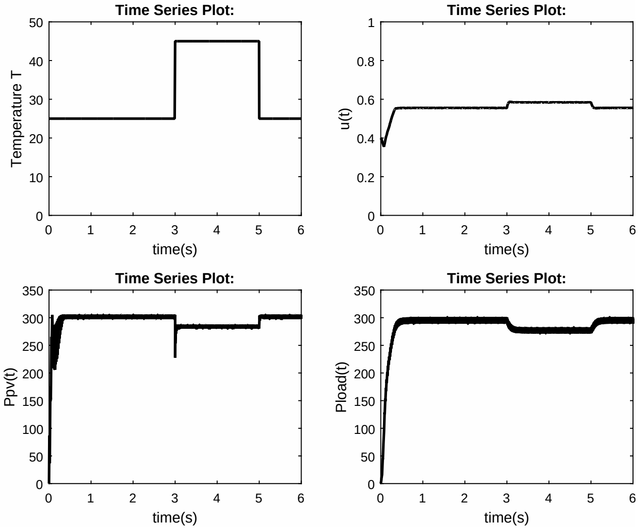

Fig. 7. MPPT control responses in case 2:T, u, P_{pv} and P_{load}.

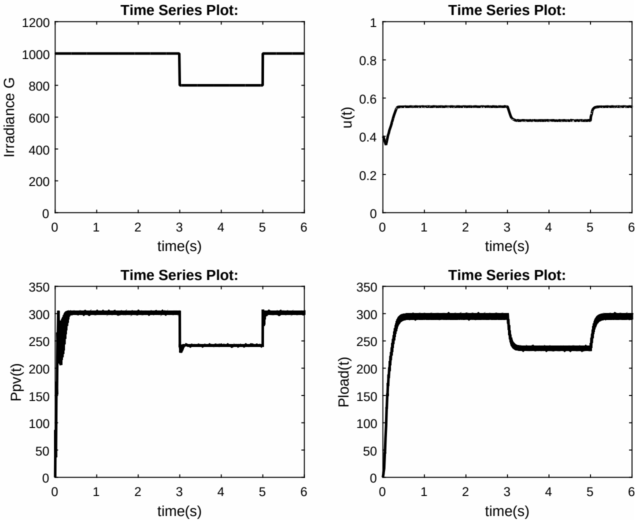

Fig. 8. MPPT control responses in case 3:G, u, P_{pv} and P_{load}.

Case 1: $G = 1000w/m^2$,$T = 25°c$.
Case 2: $G = 1000w/m^2$ with temperature variation.
Case 3: $T = 25°c$ with irradiance variation.
Fig. 6 shows the evolution responses of the control input $u(t)$ and the sliding function $s(t)$. Fig. 7 depicts the evolution responses of the temperature T, the control input $u(t)$, the output PV power P_{pv} and the load power P_{load}. Fig. 8 gives the response curves of the irradiance G, the control input $u(t)$, the output PV power P_{pv} and the load power P_{load}. It is clear that sliding mode controller quickly drives the system to the maximum power $P_{max} = 305W$. Moreover, the robust convergence of system responses in the MPPT problem is ensured by the proposed methods.

V. CONCLUSION

In this paper, the robust sliding mode control has been introduced for the maximum power tracking of PV power generation systems. By combining SMC and P&O, the controlled system assures a good MPV tracking despite of load variation and rapidly changing weather. Simulations results confirm the effectiveness of the proposed design procedure.

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