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SLIDING MODE CONTROL OF SINGLE-PHASE PV GRID-CONNECTED INVERTER

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Abstract. *In this paper, a sliding mode control (SMC) scheme is proposed to control a two-stage single-phase photovoltaic (PV) grid-connected inverter. An incremental conductance method with adaptive step size is adopted to track the maximum power point (MPP), by controlling the duty cycle of a boost DC-DC converter's controllable power switch. A sliding mode controller with an integral sliding surface is developed in the grid-connected inverter. Finally, simulation results for a PV grid-connected system built in Simulink show the effectiveness of the proposed method.*
Keywords: Sliding mode control, PV grid-connected inverter, Maximum power point

1. **Introduction.** Nowadays, PV power generation has attract much attention, and PV grid connected technology has become a hot research topic. Since the PV power generation has the characteristics of being intermittent and unstable, higher requirements are put forward about the control of PV grid-connected inverter.

A typical two-stage single-phase PV grid-connected system mainly involves two key technologies: maximum power point tracking (MPPT) and DC-AC inverter control. Common MPPT control method such as constant voltage tracking (CVT), incremental conductance method [1], perturbation and observation method [2], and intelligent methods such as fuzzy control [3], neural network [4], and particle swarm optimization [5] are proposed to track the MPP to increase the efficiency of the PV system. CVT scheme is just a means of voltage stabilizing strategy rather than MPPT; perturbation and observation method may oscillate around the MPP; intelligent methods have satisfactory adaptability to the environment condition, but the control algorithm is complex requiring high performance hardware equipment. Many schemes are presented to control the grid-connected inverter. Chen et al. [6] designed a robust fuzzy controller for PV power inverter with Taguchi tuned scaling factors. Some scholars have employed SMC to control inverter since sliding mode control (SMC) is a nonlinear control method with strong robustness to system uncertainties [7]. Islam et al. [8] proposed an improved sliding mode based inverter controller for PV system. Kumar et al. [9] proposed a novel robust and adaptive sliding-mode control for a cascaded two-level inverter-based grid-connected PV system. Dhar and Dash [10] adopted an adaptive finite time fast terminal sliding mode controller in voltage source converter.

In this paper, a typical two-stage single-phase PV grid-connected inverter is presented. An incremental conductance (INC) method with an adaptive step size is used to track the MPP and a sliding mode controller is employed to control the grid-connected inverter. The MPPT and DC-AC inverter are both controlled independently using two different strategies, while most of the existing works only do one of the two key technologies. How an operation of a small scale PV system connected to a microgrid can be achieved is described. The rest of this paper is organized as follows. Section 2 describes a model of a two-stage single-phrase PV grid-connected system. In Section 3, an INC scheme with an adaptive step size is given to track the MPP. In Section 4, SMC strategy is derived to control the DC-AC inverter. Simulation results followed by discussions are presented in Section 5 to verify the effectiveness of the proposed control strategy. Finally, conclusions are drawn in Section 6.

2. Single-Phase PV Grid-Connected System Model. A two-stage single-phase PV grid-connected inverter is shown in Figure 1. The model mainly consists of DC-DC converter and DC-AC inverter. Through DC-DC part the PV output voltage can be enlarged and MPPT schemes can be applied. DC-AC inverter turns DC power into AC power. As shown in Figure 1, boost converter is composed of a controllable power switch S_b, inductor L_{pv}, capacitor C_{dc} and diode D_{pv}. The DC-AC inverter consists of four controllable power switches. S_1, S_4 and S_2, S_3 form two group arms, by controlling the duty cycle of the two group switches, and the AC output voltage can be obtained. L_{ac}, C_{ac} are inductor and capacitor of the AC side, and R_L is the load at the grid side.

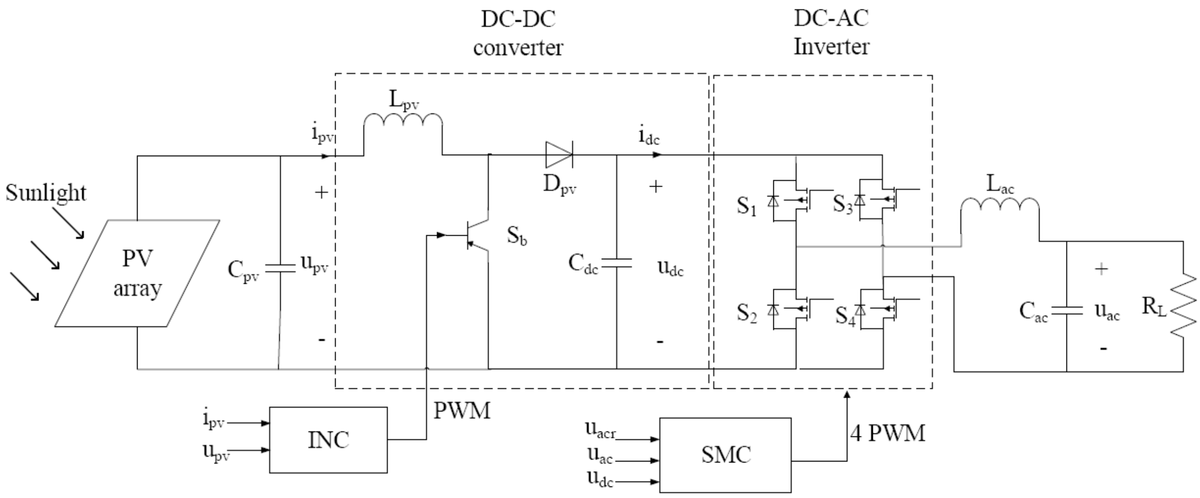

FIGURE 1. Single-phase PV grid-connected system model

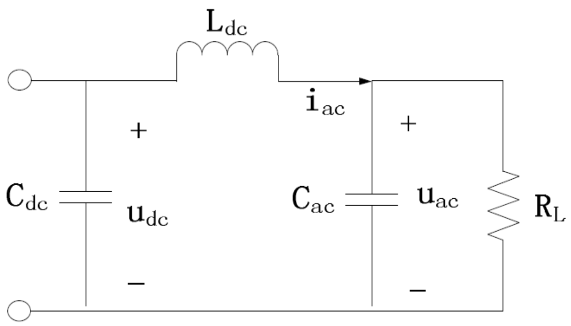

FIGURE 2. While S_1, S_4 are on

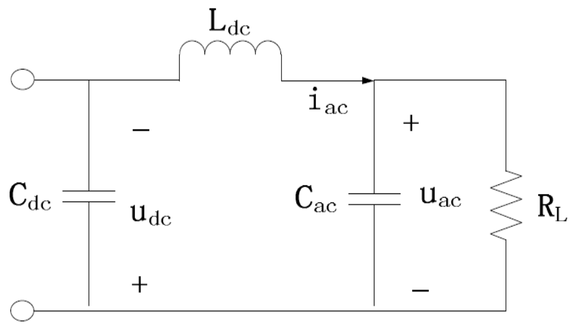

FIGURE 3. While S_2, S_3 are on

In order to establish the mathematical model of the inverter, some components need to be idealized. Assuming that S_1-S_4 are all ideal switches, whose on-resistance is close to zero, the dead time and capacitance and inductance effect can be ignored; and the parasitic resistance of inductor L_{ac} and capacitor C_{ac} is small enough. The ideal dynamic mathematical model when S_1, S_4 and S_2, S_3 are on is shown in Figure 2 and Figure 3, respectively. According to Kirchhoff's laws, we have

$$\text{While } S_1,\ S_4 \text{ are on: } \begin{cases} -u_{dc} + L_{ac}\dfrac{di_{ac}}{dt} + u_{ac} = 0 \\ i_{ac} - \dfrac{1}{R_L}u_{ac} - C_{ac}\dfrac{du_{ac}}{dt} = 0 \end{cases} \tag{1}$$

$$\text{While } S_2,\ S_3 \text{ are on: } \begin{cases} u_{dc} + L_{ac}\dfrac{di_{ac}}{dt} + u_{ac} = 0 \\ -i_{ac} + \dfrac{1}{R_L}u_{ac} + C_{ac}\dfrac{du_{ac}}{dt} = 0 \end{cases} \tag{2}$$

Assuming that D is the duty cycle of S_1 and S_4, then the duty cycle of S_2 and S_3 is $1 - D$. Combining (1) and (2), we get the mathematical expression of the inverter as (3)

$$\begin{cases} L_{ac}\dfrac{di_{ac}}{dt} = (2D-1)u_{dc} - u_{ac} \\ C_{ac}\dfrac{du_{ac}}{dt} = i_{ac} - \dfrac{1}{R_L}u_{ac} \end{cases} \tag{3}$$

Retaining the variable u_{ac}, (3) can be derived as (4)

$$\frac{d^2u_{ac}}{dt^2} = -\frac{1}{R_LC_{ac}}\frac{du_{ac}}{dt} - \frac{1}{L_{ac}C_{ac}}u_{ac} + \frac{2D-1}{L_{ac}C_{ac}}u_{dc} \tag{4}$$

Since u_{ac} and its derivative can be measured, Equation (4) has practical significance. In practical applications, the inverter is affected by parameter variations and external disturbances. Considering the nonlinearities in the inverter model, (4) can be rewritten as

$$\frac{d^2u_{ac}}{dt^2} = -\left(\frac{1}{R_LC_{ac}} + \Delta_1\right)\frac{du_{ac}}{dt} - \left(\frac{1}{L_{ac}C_{ac}} + \Delta_2\right)u_{ac} + \frac{2D-1}{L_{ac}C_{ac}}u_{dc} + d(t) \tag{5}$$

where Δ_1 and Δ_2 are the parameter variations, and $d(t)$ is external disturbance term.

Choosing state variables as: $\begin{cases} x_1 = u_{ac} \\ x_2 = \dot{u}_{ac} \end{cases}$, and setting $g(t) = -\Delta_1 x_2 - \Delta_2 x_1 + d(t)$, then the state equation of inverter, and the mathematical model of the inverter with the system nonlinearities can be described as follows:

$$\begin{cases} \dfrac{dx_1}{dt} = x_2 \\ \dfrac{dx_2}{dt} = -\dfrac{1}{R_LC_{ac}}x_2 - \dfrac{1}{L_{ac}C_{ac}}x_1 + \dfrac{2D-1}{L_{ac}C_{ac}}u_{dc} + g(t) \end{cases} \tag{6}$$

3. **MPPT Strategy.** In the practical applications, the PV system might be affected by the environment factors, and MPPT is needed to improve the efficiency of the PV system. In order to track the MPP, it is necessary to study the characteristics of PV module. The P-U characteristics of PV are shown as Figure 4.

It can be concluded that at the MPP

$$dP/dU = I + U * dI/dU = 0 \tag{7}$$

Rewrite (7) as

$$dI/dU = -I/U \tag{8}$$

The essence of searching the MPP by the INC scheme is to search the working point that satisfies Equation (8). In numerical algorithm

$$\begin{cases} dI = I(k) - I(k-1) \\ dU = U(k) - U(k-1) \end{cases} \tag{9}$$

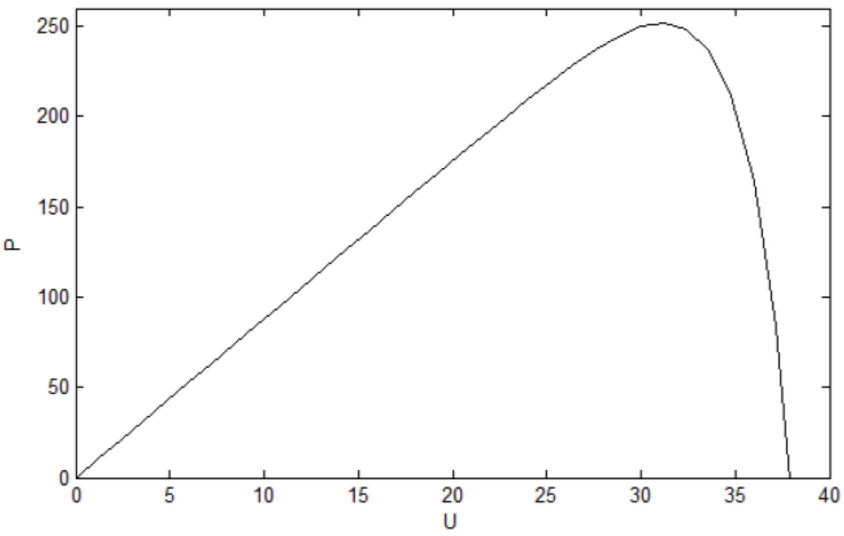

FIGURE 4. P-U characteristics of PV module

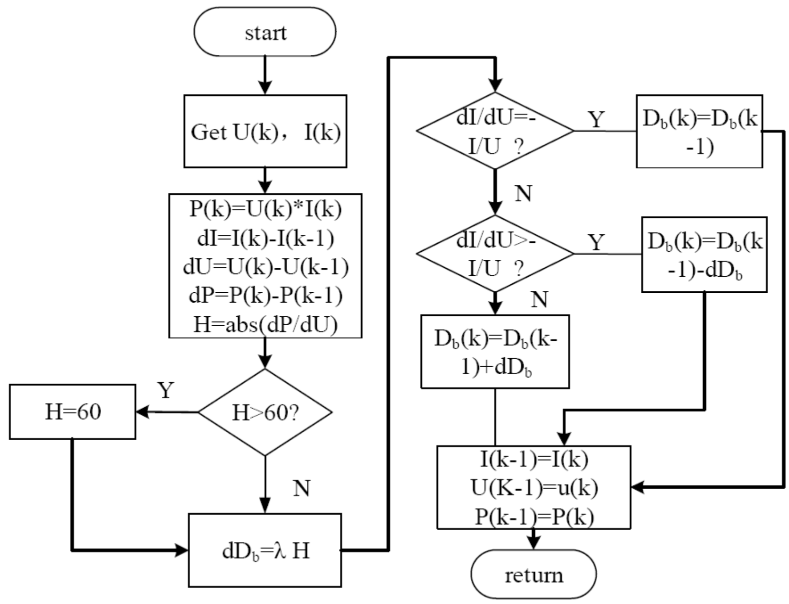

FIGURE 5. INC scheme with adaptive step size

In PV system, the boost converter satisfies the equation $U_{pv} = (1 - D_b)U_{dc}$, where D_b is the duty cycle of the switch S_b. When U_{dc} keeps constant, the PV output voltage U_{pv} and D_b vary conversely. By adjusting D_b, we can get the U_{pv} which makes the PV system work with the maximum power.

From the P-U characteristics shown in Figure 4, it can be concluded of three situations: when $dP/dU > 0$, that is $dI/dU > -I/U$, the working point locates on the left side of the MPP, and we need to reduce the D_b to increase U. When $dP/dU < 0$, that is $dI/dU < -I/U$, the current working point locates on the right side of the MPP, and we need to increase D_b to decrease U. When $dP/dU = 0$, that is $dI/dU = -I/U$, the current working point is the MPP.

Choosing adaptive step size as $\lambda \times |dP/dU|$, where λ is a positive constant, then the iteration algorithm using this step size is expressed as (10)

$$D_b(k) = D_b(k-1) \pm \lambda\,|dP/dU| \tag{10}$$

The sign in (10) is determined by the working point of the PV system. Detailed strategies are shown in Figure 5.

4. **Sliding Mode Control (SMC).** SMC is a special nonlinear control method, the structure of the system is not fixed, but adjust itself to follow the designed sliding mode according to the current state of the system in the dynamic process. It presents notable robustness in disturbance rejection because the sliding mode can be designed. Grid-connected inverter is a tracking system, whose goal is to adjust the output voltage of the inverter tracking the grid reference voltage.

The control strategy is as follows: selecting an integral sliding surface, then calculate the equivalent control law by setting $\dot{s} = 0$ without considering the nonlinearities. A switching control law is adopted to compensate the nonlinearities. The block diagram of the control algorithm is shown in Figure 6. Firstly, selecting an integral sliding surface, then calculate the equivalent (EQ) control law by setting $\dot{s} = 0$ without considering the nonlinearities. After that, a switching (SW) control law is employed to compensate the unknown nonlinearities.

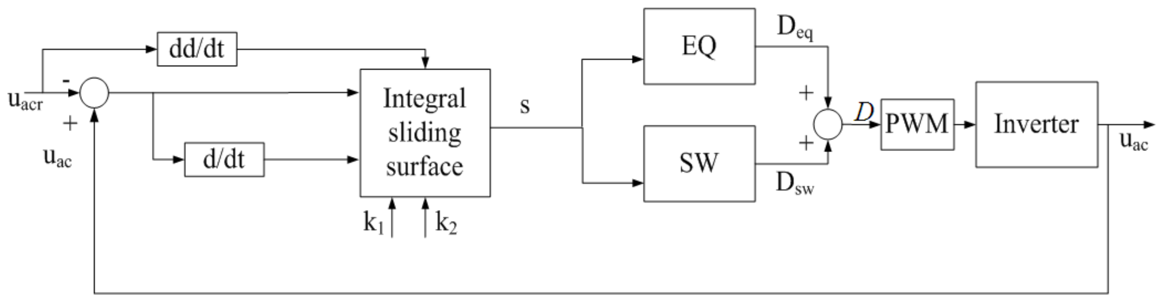

FIGURE 6. Control block diagram of PV grid-connected inverter

The first step of sliding mode control is to select a sliding surface, and then design control law such that the system state trajectories are forced toward the sliding surface and stay on it. Now, design an integral sliding surface as

$$s(t) = \dot{u}_{ac}(t) - \int_0^t \left[\ddot{u}_{acr}(t) - k_1\dot{e}(t) - k_2 e(t)\right] dt \tag{11}$$

where u_{acr} is the grid reference voltage, $e = u_{ac} - u_{acr}$ is the tracking error between u_{ac} and u_{acr}, and k_1, k_2 are positive constants.

Then the derivative of sliding surface is obtained as

$$\begin{aligned} \dot{s} &= \ddot{u}_{ac} - \ddot{u}_{acr} + k_1\dot{e} + k_2 e \\ &= -\frac{1}{R_L C_{ac}}\dot{u}_{ac} - \frac{1}{L_{ac}C_{ac}}u_{ac} + \frac{2D-1}{L_{ac}C_{ac}}u_{dc} + g - \ddot{u}_{acr} + k_1\dot{e} + k_2 e \end{aligned} \tag{12}$$

Setting $\dot{s} = 0$ and ignoring g, we get the equivalent control D_{eq} as

$$D_{eq} = 0.5\left[1 + \frac{L_{ac}C_{ac}}{u_{dc}}\left(\frac{1}{R_L C_{ac}}\ddot{u}_{ac} + \frac{1}{L_{ac}C_{ac}}u_{ac} + \ddot{u}_{acr} - k_1\dot{e} - k_2 e\right)\right] \tag{13}$$

By choosing suitable k_1, k_2, the condition $\dot{s} = 0$ can be satisfied.

The control law described by (13) should be updated because the nonlinearities are ignored. So a realistic control law is designed as

$$D = D_{eq} + D_{sw} \tag{14}$$

$$D_{sw} = -0.5 * \frac{L_{ac}C_{ac}}{u_{dc}} g_E \operatorname{sgn}(s) \tag{15}$$

where $|g| < g_E$, g_E is the upper bound of system uncertainties. The switching control law is adopted to compensate the system nonlinearities to ensure the sliding condition can be always satisfied so that the stability of the system can be guaranteed.

Select a Lyapunov function as

$$V = \frac{1}{2}s^2 \tag{16}$$

Differentiating (16) with respect to time, we have

$$\dot{V} = s\dot{s} = -(g_E - g)|s| \leq 0 \tag{17}$$

$\dot{V}$ is negative semi-definite, which implies that the system can be asymptotically stable according to Lyapunov stability theorem. Furthermore, according to the Barbalat lemma, it can be concluded that the tracking error $e \to 0$ as $t \to \infty$, which means the output of inverter can track the grid reference voltage with zero steady state error.

5. Simulation Study.

In order to verify the effectiveness of the proposed control strategy, the simulation model is built in Simulink according to the control structure in Figure 1. A 500W PV model is established in simulation. Simulation parameters are set as Table 1.

Table 1. Simulation parameters

Parameters	Values	Parameters	Values
u_{acr}	$220\sqrt{2}\sin(100\pi t)$	η	6×10^6
C_{ac}	$2.82 \times 10^{-5}F$	L_{pv}	$3 \times 10^{-4}H$
L_{ac}	$0.048H$	C_{pv}	$10^{-3}F$
R_L	400Ω	C_{dc}	$10^{-4}F$
k_1, k_2	8×10^4, 5×10^8	λ	10^{-6}

In practical applications, the PV modules are sensitive to the change of light intensity and environment temperature. In order to verify the feasibility of the proposed strategies, we change the light and temperature factor in simulation. The variations of the light and temperature are shown in Figure 7, where Y-label S represents the light intensity and T is the temperature of PV.

Figure 8 shows the dynamic processes of the power and voltage of the PV array with environmental changes. It can be found that the proposed MPPT method can adapt the environment's variations and track the MPP quickly.

Tracking processes shown in Figure 9 depict that the inverter can track the grid reference voltage quickly with zero tracking error. The variations of environment factors have no significant influence on the AC voltage of inverter, showing the robustness of the proposed strategy. Figure 10 draws the power factor of grid inverter, showing the proposed

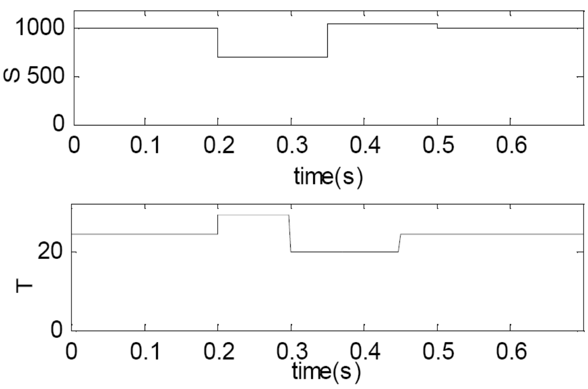

Figure 7. Variations of the light and temperature

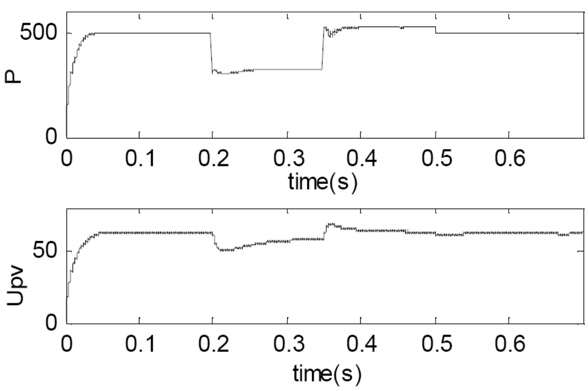

Figure 8. MPPT performance

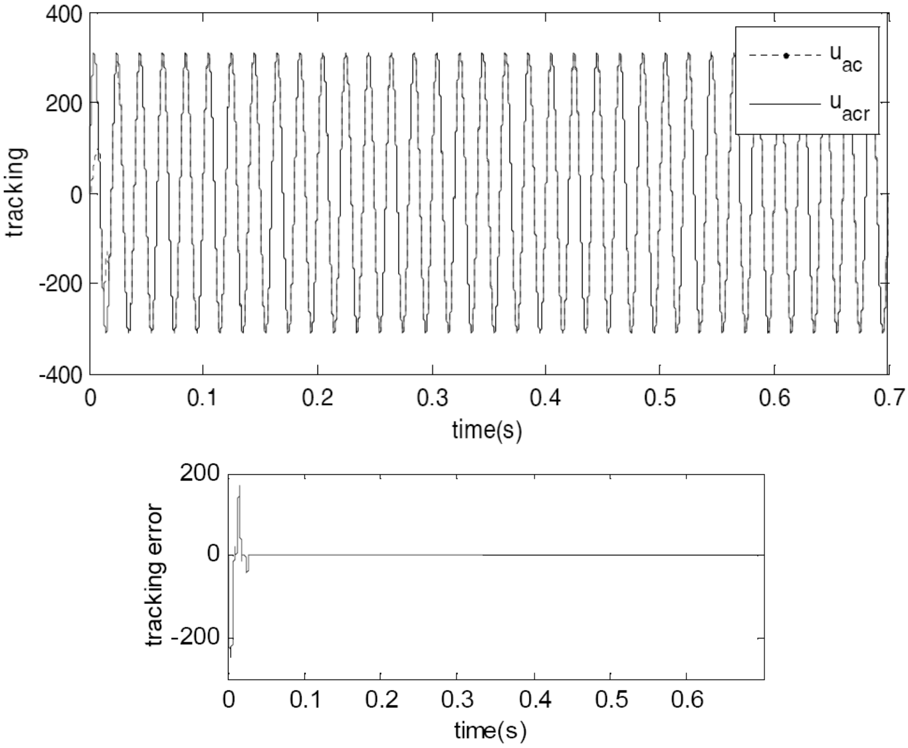

Figure 9. Voltage tracking performance of inverter

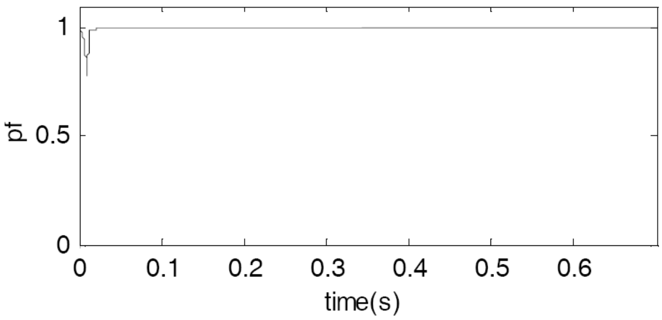

Figure 10. Power factor of inverter

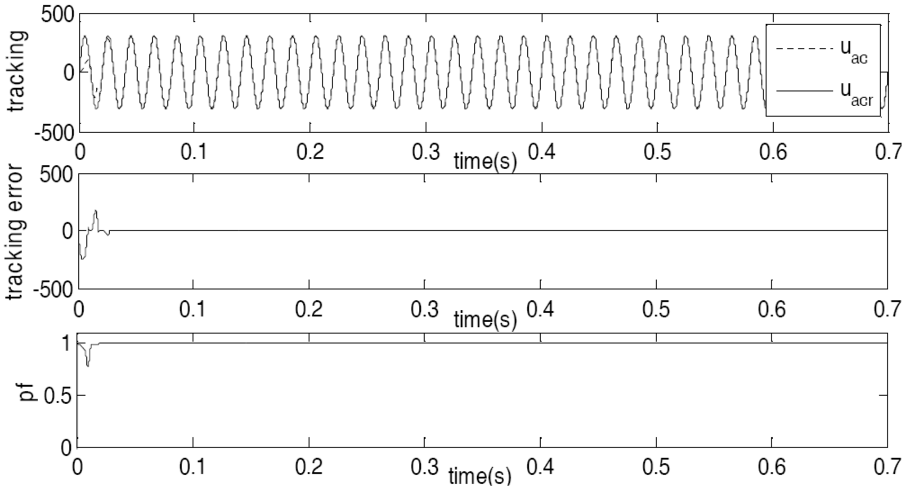

Figure 11. Tracking performance using SMC

control strategy can achieve unity power factor with no reactive power loss. The tracking performance of sliding mode control (SMC) is drawn in Figure 11.

6. **Conclusions.** In this paper, the MPPT and the DC-AC inverter control strategy are implemented on a small scale two-stage grid-connected PV inverter system. In practical applications, the PV system will be affected by the environmental factors such as the light intensity and temperature. The simulation results show that the maximum output power of PV system is greatly influenced by the variations of light intensity and temperature, fortunately, the proposed incremental conductance method with adaptive step size can adapt to the environment changes and track the maximum power point quickly; grid-connected inverter voltage is not affected by the impact of environmental changes, indicating the robustness of the proposed SMC strategy. In the future work, we prepare to combine some intelligent control methods with SMC to control the PV grid-connected inverter to achieve more satisfactory performance.

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