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Modeling of Grid-Connected Inverter and Stability Analysis in DC-Link Voltage Control using Fuzzy Adaptive SMC System

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ABSTRACT: In this paper, an adaptive fuzzy sliding mode controller is proposed to control a three-stage single-phase Photovoltaic (PV) grid-connected inverter. Two key technologies are discussed in the presented PV system. An incremental conductance method with adaptive step is adopted to track the Maximum Power Point (MPP) by controlling the duty cycle of the controllable power switch of the boost DC-DC converter. An adaptive fuzzy sliding mode controller with an integral sliding surface is developed for the grid-connected inverter where a fuzzy system is used to approach the upper bound of the system nonlinearities. The proposed strategy has strong robustness for the sliding mode control can be designed independently and disturbances can be adaptively compensated. Simulation results of a PV grid-connected system verify the effectiveness of the proposed method, demonstrating the satisfactory robustness and performance.

KEYWORDS: Inverters, Topology, Capacitors, Insulated gate bipolar transistors, Power harmonic filters, Photovoltaic systems, Voltage control.

I.INTRODUCTION

With the depletion of traditional energy sources, the research of energy management [1] [2] and the development of new energy have aroused the interest of researchers. New energy has attracted widespread attention because of its characteristic of being clean and renewable. Sun et.al [3] employed a nonlinear data-enabled predictive energy management strategy for a residential building with PV and battery energy storage using model predictive controller with nonlinear PV and battery models, and a Radial Basis Function – Neural Network (RBF-NN) load forecasting algorithm. A key novelty in [3] is to close the gap between building energy management formulations, advanced load forecasting techniques, and nonlinear battery/PV models.

With the development of new energy technologies, PV grid-connected technology has become a hot research topic, more and more people pay attention to the PV power generation. Since PV generation has the characteristics of being intermittent and unstable, higher requirements are put forward about the control of the 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) [4], Incremental Conductance (INC) method [5][6], perturbation and observation method [7], and intelligent methods such as fuzzy control[8], neural network [8] particle swarm optimization are proposed to track the MPP to increase the efficiency of the PV system. The CVT scheme, which ignores the influence of environment factors, is just a means of voltage stabilizing strategy rather than the MPPT, having low precision and poor adaptability; perturbation and observation method may oscillate in the vicinity of the maximum power point; intelligent methods have satisfactory adaptability to the environment conditions, however the control algorithm is complicated.

Intelligent methods are employed to serve grid-connected inverters. Chen et al. [13] designed a robust fuzzy controller for a PV power inverter with Taguchi tuned scaling factors, easy to be implemented. Logeswaran et al. [14] presented an adaptive neuro-fuzzy model to a multilevel inverter for grid-connected PV system. These strategies are novel to the grid-connected inverter, but there is no discussion about the performance under environmental variations since the PV modules is sensitive to the environment factors such as solar level and environment temperature.

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In this section, a two-stage single-phase PV grid-connected inverter model is described and the mathematical expression of the inverter is established, then the INC MPPT scheme is presented to track the MPP of the PV system, the strategy is proposed to control the inverter based on Lyapunov theorem.

II.PV GRID-CONNECTED MODEL

As shown in Fig 1, PV grid-connected inverter mainly consists of two parts: DC-DC converter and DC-AC inverter. Through the boost DC-DC converter, the PV output voltage can be enlarged and MPPT schemes can be applied. DC-AC inverter turns DC power into AC power with the same frequency and phase with the grid reference voltage

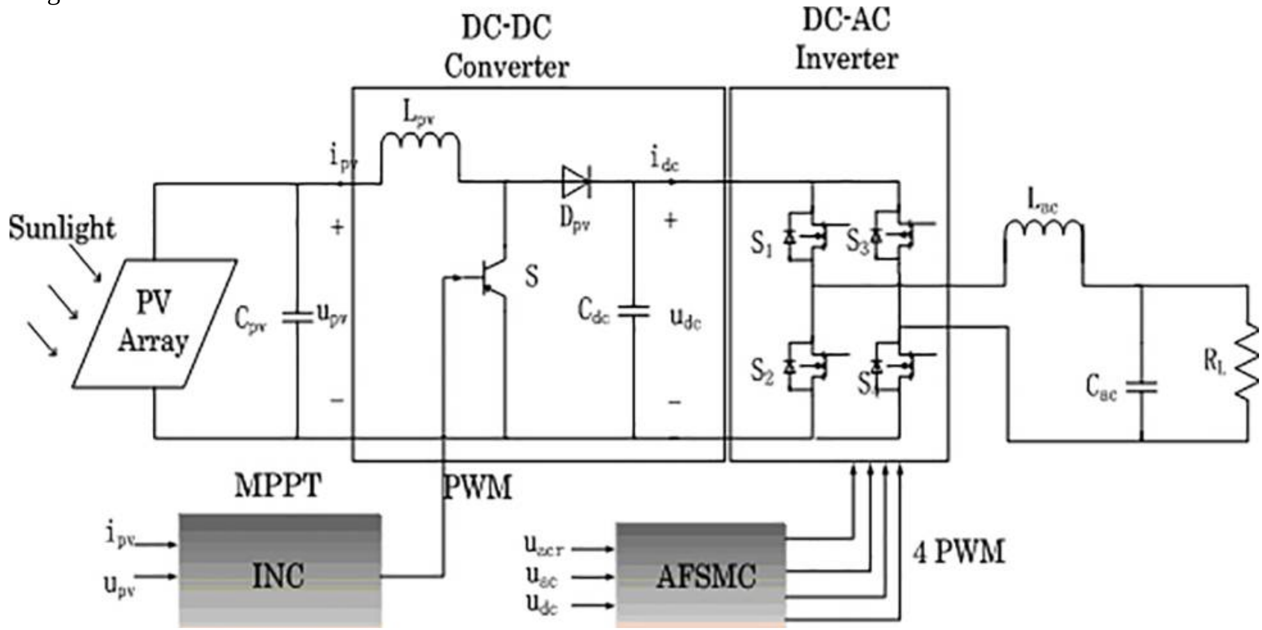

Fig 1. Three PV grid-connected system model.

The boost converter is composed of a controllable power switch S_b, inductor L_{pv}, capacitor $C_{dc}$and diode D_{pv}. By adjusting the duty cycle of switch S_b, the PV system can work at the MPP. The H-bridge DC-AC inverter consists of four controllable power switches. S_1, *S4* and S_2, *S3form* two group arms respectively, by controlling the duty cycle of the two groups of switches, the AC voltage can be obtained. L_{ac}, C_{ac} are inductor and capacitor at the AC side, R_L is the load.

In order to establish the mathematical expression of the inverter, some components need to be idealized. Assuming that S_1−S_4 are all ideal switches with zero on-resistance, whose dead time and capacitance and inductance effect can be ignored, assuming the parasitic resistance of inductor L_{ac} and capacitor C_{ac} is small enough. The equivalent circuit when the two groups of switch S_1, *S4* and S_2, *S3* are on is shown in Fig 2 and Fig 3 respectively.

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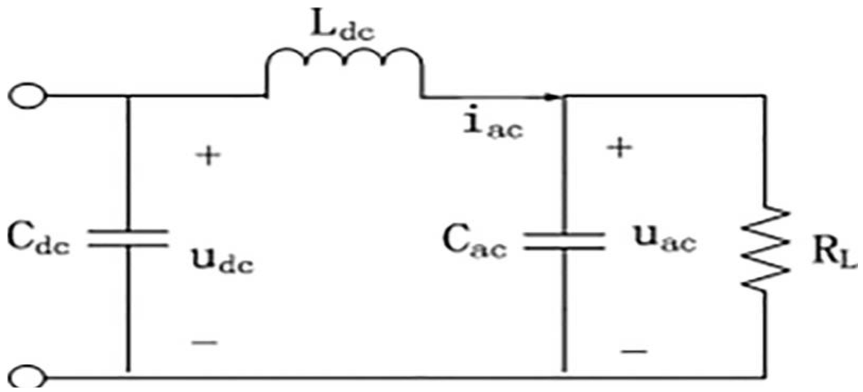

Fig 2. Case while S1, S4 are on

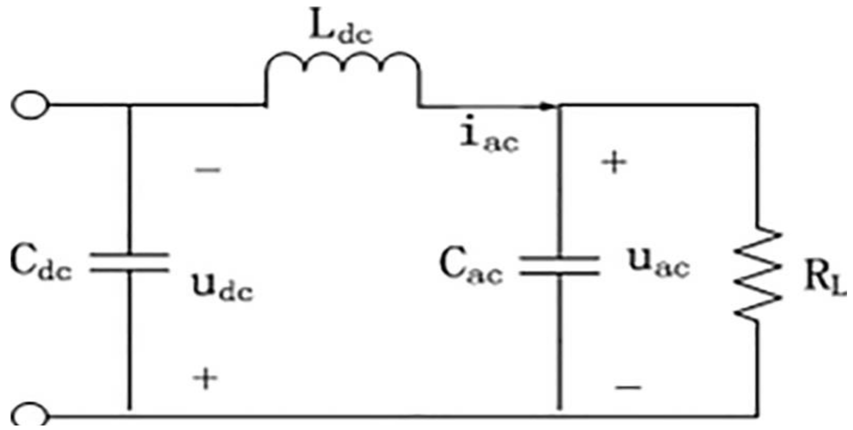

Fig 3. Case while S2, S3 are on

According to according to Kirchhoff's voltage law (KVL) and Kirchhoff's current law (KCL), we have

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), the

$$-u_{dc} + L_{ac}\frac{di_{ac}}{dt} + u_{ac} = 0$$

While

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

mathematical expression of the inverter can be described as (3)

After elimination and consolidation, the dynamic equation of the inverter is derived as (4)

$$\frac{d^2u_{ac}}{dt^2} = -\frac{1}{R_L C_{ac}}\frac{du_{ac}}{dt} - \frac{1}{L_{ac}C_{ac}}u_{ac} + \frac{2D-1}{L_{ac}C_{ac}}u_{dc} \quad (4)$$

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Since u_{ac} and its derivative as well as the DC side voltage u_{dc} can be measured and provided to the controller, the Eq (4) has practical significance. In practical applications, the inverter is affected by parameter variations and external disturbances such as environmental variations, as a result, the expression of (4) cannot represent the model of real inverter any longer, so (4) need to be modified. Considering the nonlinearities in the inverter model, then the mathematical expression of the inverter is obtained as (5)

$$\frac{d^2u_{ac}}{dt^2} = -\frac{1}{R_L C_{ac}}\frac{du_{ac}}{dt} - \frac{1}{L_{ac}C_{ac}}u_{ac} + \frac{2D-1}{L_{ac}C_{ac}}u_{dc} + g(t) \quad \textbf{(5)}$$

Where g (t) is the system unknown nonlinearities.

III.DESIGN OF ADAPTIVE FUZZY SLIDING MODE CONTROL

Sliding Mode Control (SMC) is a special nonlinear control method with notable robustness in disturbance rejection because the sliding mode can be designed without the information of nonlinearities. Grid-connected inverter is a tracking system, whose goal is to track the grid reference voltage.

The algorithm is shown in 4. Firstly, select an integral sliding surface, then calculate the equivalent (EQ) control law by setting $\dot{s} = 0$ without considering the nonlinearities. After that, employ a switching (SW) control law to compensate the unknown nonlinearities. Finally, adopt a fuzzy system to estimate the upper bound of the nonlinearities.

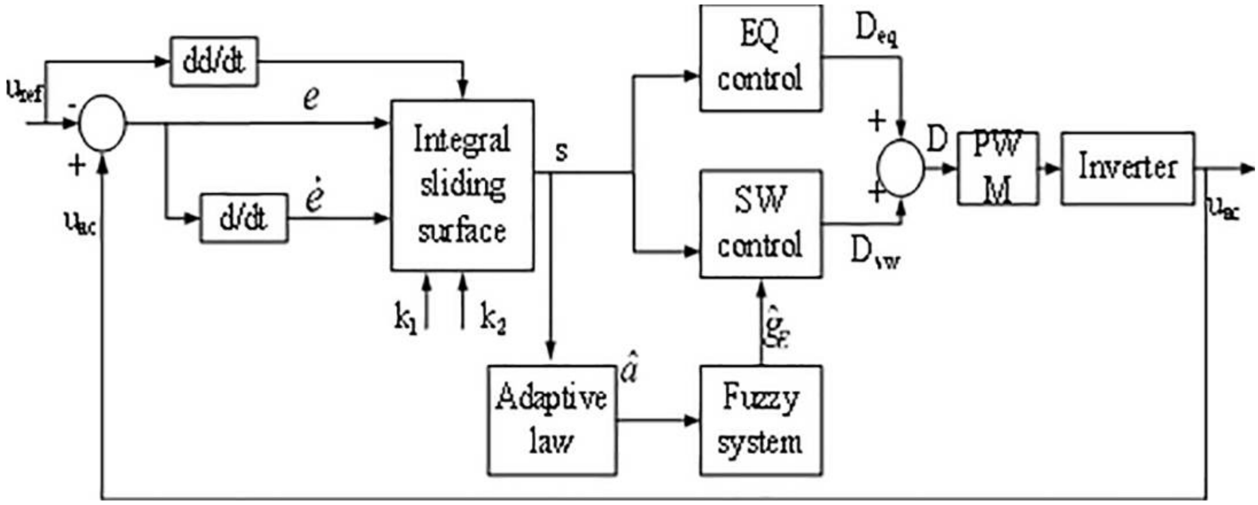

Fig 4. Block diagram of AFSMC

IV.ADAPTIVE FUZZY SLIDING MODE CONTROL

In fact, the upper bound of the system nonlinearities is difficult to be measured in practical applications, if an empirical value is selected, then too large value may result in large oscillation, while too small one will not be able to compensate the nonlinearities. So a fuzzy system is proposed to approach the optimal upper bound of the nonlinearities adaptively. Fig.5 shows the proposed system.

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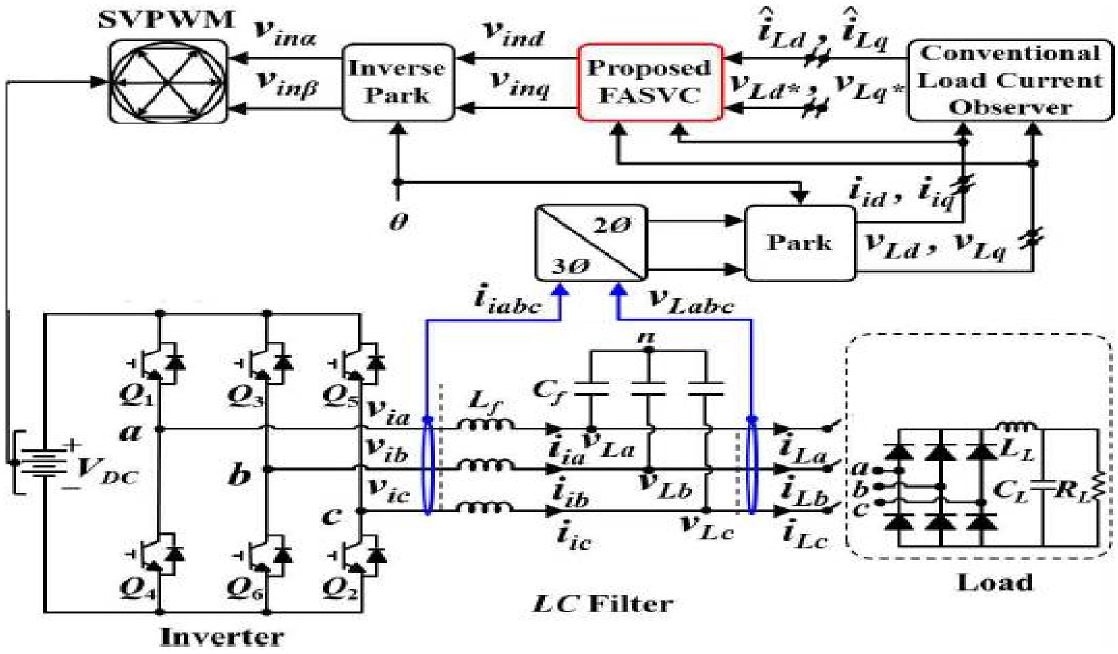

Figure: 5 Proposed design

Choosing the tracking error e as the input and the upper bound of uncertainties g_E as the output to form a single input and single output fuzzy system with the fuzzy rules as follows: Rule i : If e is F_e^i, then g_E is a_i

where F_e^i (i = 1,2,3……m) and a_i (i = 1,2,3…….m) belong to the fuzzy input and output set respectively, and m is the number of fuzzy rules. The defuzzification of the fuzzy output is accomplished by the method of center-of -gravity determined by (6)

$$g_E = \frac{\sum w_i \times a_i}{\sum w_i} = a^T \xi \tag{6}$$

where a is an adjustable parameter vector, ξ is a fuzzy basis function vector,

According to the universal approximation theory, there exists an optimal parameter *that* satisfied $g_E^* = g_E + \varepsilon = a^{*T}\xi$, where ε is the approximation error bounded by $|\varepsilon| < E$, E is a positive constant.

Employing an adaptive fuzzy control system to approximate the upper bound of system nonlinearities g_E is described as (7)

$$\hat{g}_E = \hat{a}^T \xi \tag{7}$$

where $\hat{a}$ is the estimation of a*.

Applying the fuzzy system (7) to estimate g_E in the switching term described by (5), replace g_E in (5) by $\hat{g}_E$, we get the new switching control law as (8)

$$D_{sw} = -0.5 * \frac{L_{ac}C_{ac}}{u_{dc}} \hat{g}_E \operatorname{sgn}(s) \tag{8}$$

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Combining (3), (4) and (8) yields

$$\begin{aligned} \dot{s} &= \ddot{u}_{ac} - \ddot{u}_{ref} + k_1\dot{e} + k_2 e \\ &= -\frac{1}{R_L C_{ac}}\dot{u}_{ac} - \frac{1}{L_{ac}C_{ac}}u_{ac} + \frac{2D-1}{L_{ac}C_{ac}}u_{dc} + g - \ddot{u}_{ref} + k_1\dot{e} + k_2 e \\ &= g - \hat{g}_E \operatorname{sgn}(s) \end{aligned} \tag{10}$$

$$D = 0.5[1 + \frac{L_{ac}C_{ac}}{u_{dc}}(\frac{1}{R_L C_{ac}}\dot{u}_{ac} + \frac{1}{L_{ac}C_{ac}}u_{ac} + \ddot{u}_{ref} - k_1\dot{e} - k_2 e - \hat{g}_E \operatorname{sgn}(s))] \tag{9}$$

Taking derivative of the sliding function and applying the control law (9), the following equation can be obtained

Define $\tilde{a} = \hat{a} - a^*$ as the error between a^* and its estimation $\hat{a}$.
Select a Lyapunov function candidate as

$$V = \frac{1}{2}s^2 + \frac{1}{2\eta}\tilde{a}^T\tilde{a} \tag{11}$$

Where η is a positive constant. Differentiating (11) with respect to time derives

$$\begin{aligned} \dot{V} &= s\dot{s} + \frac{1}{\eta}\tilde{a}^T\dot{\hat{a}} = s(g - \hat{g}_E \operatorname{sgn}(s)) + \frac{1}{\eta}\tilde{a}^T\dot{\hat{a}} = s(g - \hat{a}^T\xi \operatorname{sgn}(s)) + \frac{1}{\eta}\tilde{a}^T\dot{\hat{a}} = s(g - \hat{a}^T\xi \operatorname{sgn}(s)) - \frac{1}{\eta}(\hat{a} - a^*)^T\dot{\hat{a}} \\ &= sg - \hat{a}^T\xi|s| + \frac{1}{\eta}(\hat{a} - a^*)^T\dot{\hat{a}} = sg - \hat{a}^T\xi|s| + \frac{1}{\eta}\hat{a}\dot{\hat{a}} - \frac{1}{\eta}a^{*T}\dot{\hat{a}} \end{aligned} \tag{12}$$

To ensure $\dot{V} \leq 0$, the adaptive law is designed as (13)

$$\dot{\tilde{a}} = \dot{\hat{a}} = \eta|s|\xi \tag{13}$$

Apply (13) into (12) derives that

$$\begin{aligned} \dot{V} &= sg - |s|a^{*T}\xi \leq |s|g - |s|a^{*T}\xi \\ &= -(g_E - g + \varepsilon)|s| \leq -(g_E - |g| + \varepsilon)|s| \\ &= -(g_E - |g|)|s| - \varepsilon|s| \leq -\varepsilon|s| \\ &\leq -|\varepsilon||s| \leq 0 \end{aligned} \tag{14}$$

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

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V.SIMULATION RESULTS AND DISCUSSION

Fig. 6,7,8 shows the simulation result of proposed system. In order to verify the effectiveness of the proposed control strategies. A PV module with 500W maximum power is employed, a two-stage single-phase PV grid-connected system model is built in Simulink with the parameter. The following paragraph describes the performance of the inverter under environmental variations and the performance comparison.

Adopts a fuzzy system to estimate the upper bound of the uncertainties of the inverter system which enhances its robustness for the nonlinearities can be adaptively compensated. SMC achieve its performance by employing a switching term to compensate the impact of uncertain disturbances, and the switching gain is chosen generally large for there is no prior knowledge about the disturbance, as a result there may be large chattering in SMC. It can be concluded that the AFSMC has better tracking performance than SMC with smaller tracking error, and higher power quality.

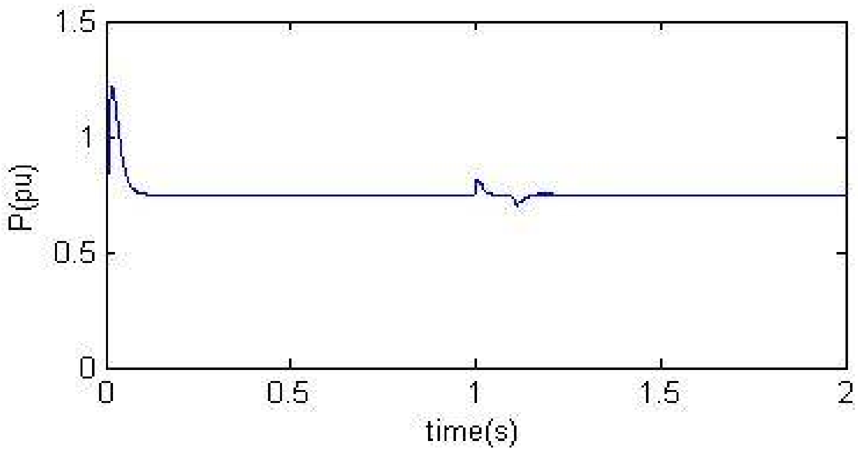
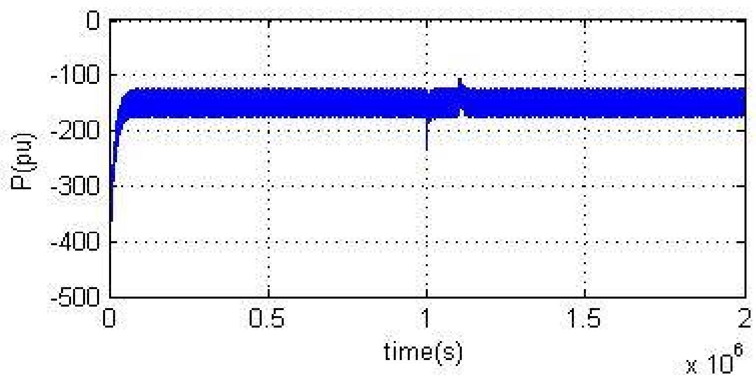


Fig.6 power waveform



(a)

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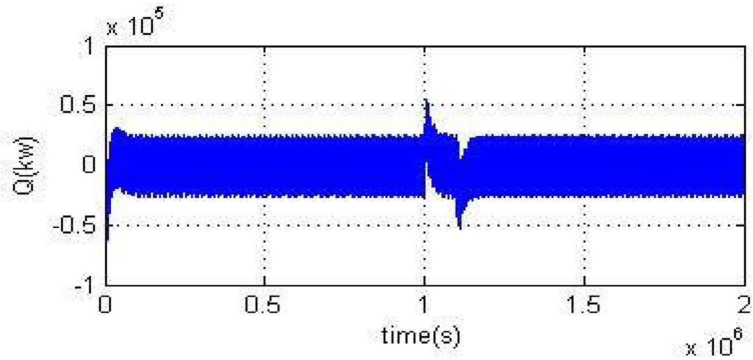
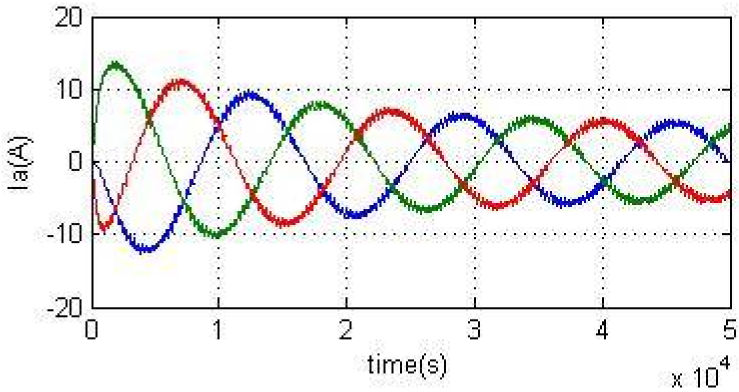
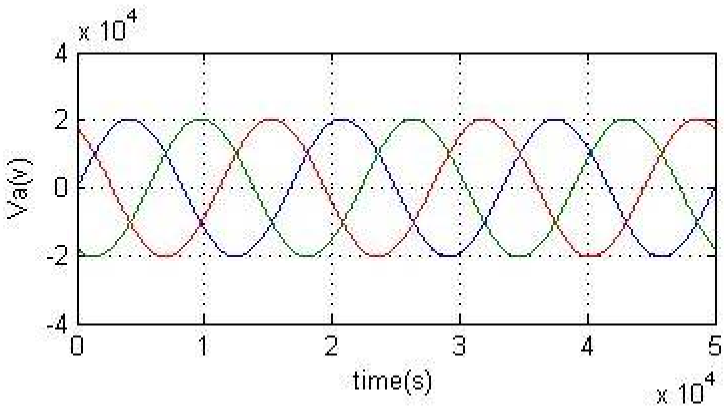


(b)

Fig. 7 (a) active power (b) reactive power



(a)



(b)

Fig. 8 (a) Current and (b) Voltage waveforms

VI.CONCLUSION

In this paper, the MPPT and the DC-AC inverter controlling are accomplished on a small scale two-stage single-phrase PV grid-connected inverter system. An INC scheme with an adaptive step size is adopted to track the maximum power point by controlling the duty cycle of the controllable power switch of the boost DC-DC converter. An adaptive fuzzy sliding mode controller with an integral sliding surface is developed for the grid-connected inverter, a fuzzy system is used to approach the upper bound of the system nonlinearities. The simulation results of MPPT

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indicate that the proposed INC strategy can be adapted to the environment variations and track the MPP quickly. The performance of voltage tracking shows that the inverter is not sensitive to the environmental variations, indicating the robustness of the proposed AFSMC scheme. Comparison results with SMC verify the superiority of the proposed AFSMC strategy.

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