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T-S Fuzzy Maximum Power Point Tracking Modelling And Control Of Solar Power Generation

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Abstract:

This paper presents maximum power point tracking (MPPT) control for stand-alone solar power generation systems via the Takagi–Sugeno (T-S) fuzzy-model-based approach. In detail, we consider a DC/DC boost converter to regulate the output power of the photovoltaic panel array. First, the system is represented by the T-S fuzzy model. Next, in order to reduce the number of measured signals, a T-S fuzzy observer is developed for state feedback. Then, a fuzzy direct MPPT controller is proposed to achieve asymptotic MPPT control, in which the observer and controller gains are obtained by separately solving two sets of linear matrix inequalities. Different from the traditional MPPT approaches, the proposed T-S fuzzy controller directly drives the system to the maximum power point without searching the maximum power point and measuring insolation. Therefore, the proposed method provides an easier implementation of modeling and controlling of maximum power tracking of solar power generation. Finally, the control performance is shown from the numerical simulation and experimental results.

***Index Terms*—Linear matrix inequalities (LMIs), maximum power point tracking (MPPT), photovoltaic (PV) array, Takagi– Sugeno (T-S) fuzzy model.**

I. INTRODUCTION

Saving Earth's energy has become an important issue in this century because energy famine will occur after a few decades. The interest in solar power has been rapidly growing due to its advantages that include:

1) Direct electric power form;
2) Little maintenance;
3) No noise;
4) No pollution.

Since solar power uses the photovoltaic (PV) effect to transform solar energy into electrical energy, the PV panel is a nonlinear power source. The output power of a PV panel array depends on the PV-voltage and unpredictable weather conditions. In order to optimize the ratio between output power and installation cost,DC/DC converters are used to draw maximum power from the PVpanel array [1], [2]. Many approaches have been proposed toadjust the tracking (MPPT), such as perturb-and-observe method, incremental conductance method, curve fitting method, fuzzy logic methods [6]–[9], neural networks, etc. Most of MPPT methods lack strict convergence analysis, and thus, only approximate MPPT is achieved. Although neural network control methods can provide better MPPT performance than traditional and fuzzy logic control methods, neural network control methods require the measurements of solar radiation and cell temperature. In addition, when the dynamics of the converter are considered, the maximum power voltage (MPV) based approaches have been developed in. The disadvantage is that two control loops are required: first, the MPV of the PV array needs to be determined, and second, the PV array voltage needs to be controlled according to the reference voltage set in the first loop. Meanwhile, the MPV is difficult to find due to rapidly changing atmospheric conditions. In other words, the implementation of these MPV-based approaches is complicated. To remove these drawbacks, only one control loop is used in by taking the maximum power condition as the control objective.

According to the Takagi–Sugeno (T-S) fuzzy model representation [8], [9], nonlinear systems can be described by IF–THEN fuzzy rules that have local linear dynamic subsystems in the consequent part. From the local linear dynamic model, linear control theory is extensively applied to nonlinear systems by using parallel distributed compensation (PDC). The main advantage is that the controller gains can be designed from linear matrix inequality (LMI) techniques. So far, the T-S fuzzy-model-based control has become a popular and effective method for controlling complex nonlinear systems. However, most results focus on the stabilization problem of nonlinear systems. Only few of the works deal with the tracking or regulation control problem. For examples, approximate tracking control is achieved by attenuating the residual tracking error. The linear regulation theories and fuzzy PDC are combined in [9] for regulation control. In addition, a non-vanishedbias at the origin and external disturbances (whichalways exist in DC/DC converters) will make PDCnontrivial, i.e.,the T-S fuzzy-model-based control cannot be directly applied tothe solar power generation system. To remove this drawback, acoordinate transformation is applied in to the converter forT-S fuzzy MPPT control of the PV system. The main disadvantageis that the operational point of the MPPT must be knownduty cycle of the converter for maximum power point exactly, in which the design failed in practical implementation. Therefore, all the earlier points motivate this study. In this paper, we develop an MPPT method for stand-alone solar power generation systems via the T-S fuzzy-model-based approach. Here the output power of the PV array is adjusted by a DC/DC boost converter. First, the system is represented in the T-S fuzzy model, where the partial derivative of the PV power with respect to the PV voltage is taken as the control output. Since typical fuzzy PDC is nontrivial to biases of the buck converter, a fuzzy *direct MPPT* (DMPPT) controller is introduced to cope with the biases and directly drive the system to the maximum power point. Meanwhile, we develop a fuzzy observer for state feedback under partial state measurement. The proposed fuzzy DMPPT controller provides asymptotic MPPT for solving an LMI problem. Then, a robust MPPT design is carried out to achieve disturbance/uncertainty attenuation. The main contributions of this paper include the following.

1) The calculation for the maximum power operational point of the converter is not required.
2) Coordinate transformation is not performed for the T-S fuzzy MPPT control.
3) Asymptotic MPPT is assured even with rapidly changing atmospheric conditions.
4) Measurement of insolation is not needed.
5) The method has a systematic design and strict stability analysis.

The rest of the paper is organized as follows. Section II starts with the T-S fuzzy modeling of solar power generation systems. In Section III, we propose the fuzzy DMPPT controller design. To show the control performance, numerical simulations and experiments are performed in Sections IV and V, respectively. Finally, some conclusions are drawn in Section VI.

II. FUZZY MODELING OF THE SOLAR POWER GENERATION SYSTEM

Without loss of generality, the solar power generation systemconsidered here consists of a PV array and a DC/DC buckconverter. The system is depicted in Fig. 1, and its detailedcharacteristics are stated in the following sections.

A. Solar Photovoltaic Array

Consider a PV panel array composed of solar cells arrangedin an n_p-parallel, n_s-series configuration. Let *v*pv and *i*pv, respectively,denote the output voltage and current of the PVarray.

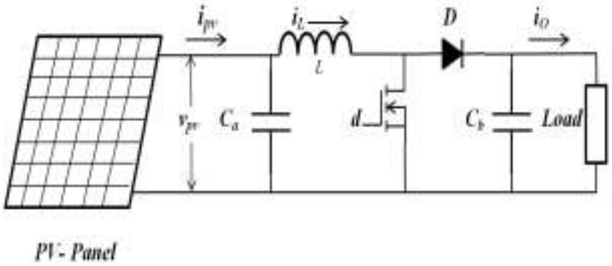


Fig. 1 Configuration of the solar power generation system.

The voltage/current characteristic equation of the PV array canbe described by a light-generated current source and a diode. Ifthe internal shunt and series resistances are neglected, the outputcurrent of the PV array is given by

$$i_{pv} = n_p I_{ph} - n_p I_{rs}(e^{\frac{k_{pv} v_{pv}}{n_s}} - 1) \qquad (1)$$

wherek_{pv} = *q*/(*pKT*) with the electroniccharge *q* = 1.6 × 10−19 C, Boltzmann's constant *K* = 1.3805 × 10−23 J/K, celltemperature *T*, and the ideal p-n junction characteristic factor*p* = 1–5, I_{ph} is the light-generated current, and I_{rs}denotesthe reverse saturation current. Besides, the reverse saturationcurrent and the light-generated current depend on insolationand temperature with the following expressions:

$$I_{rs} = I_{rr}(\frac{T}{T_r})e^{qE_{gp}(\frac{1}{T_r}-1/T)/pK} \qquad (2)$$

$$I_{ph} = (I_{sc} + K_I(T - T_r))\frac{\lambda}{100} \qquad (3)$$

where$I_{rr}$is the reverse saturation current at the reference temperatureT_r, E_{gp}= 1.1 eV is the bandgap energy of the semiconductormaking up the cell, I_{sc} is the short-circuit cell currentat reference temperature and insolation, K_I(in milliamperesper kelvin) is the short-circuit current temperature coefficient,and λ is the insolation (in milliwatts per square centimeter). The expression of the array power is obtained as follows:

$$P_{PV} = i_{pv} v_{pv} = n_p I_{ph} v_{pv} - n_p I_{rs} v_{pv}(e^{k_{pv} v_{pv}/n_s} - 1) \qquad (4)$$

According to this equation, Fig. 2 depicts the characteristics ofthe array power with respect to the PV voltage, the insolation,and cell temperature. It can be observed that the maximumpower point is maximized by the PV voltage and is dependenton various insolation and temperature.According to the array power (4) and by taking the partialderivative of P_{pv} with respect to the PV voltage v_{pv} , we obtain

$$\frac{dP_{PV}}{dv_{PV}} = i_{pv} + v_{pv}\frac{di_{pv}}{dv_{pv}}$$

$$\frac{dP_{PV}}{dv_{PV}} = i_{pv} - \frac{n_p k_{pv}}{n_s} I_{rs} v_{pv} e^{k_{pv} v_{pv}/n_s} \qquad (5)$$

The maximum power point satisfies the condition dP_{pv}/dv_{pv} = 0. However, due to the high nonlinearity, the maximum power point is difficult to be solved from (5). This is the reason why the MPPT cannot be achieved easily (practically, $dP_{pv}/dv_{pv} \sim= 0$ is used in traditional methods [2], [6]).

Table I Specification of PV Module SP75

Electrical Characteristics	Numerical value
Maximum power (Pmax)	75W
Voltage at Pmax (Vmp)	17V
Current at Pmax (lmp)	4.4A
Warranted minimum Pmax	45W
Short-circuit current (Isc)	4.8A
Open-circuit voltage (Voc)	21.7
Temperature coefficient of Isc	2.06mA /°C
Temperature coefficient of	-(0.077)mV/°C
Temperature coefficient of	-(0.5±0.05)%/°C

B. DC/DC Boost Converter

To adjust the PV array power, a DC/DC boost converter is connected to the PV array, as shown in Fig.1. The dynamic model of the converter can be described by the state equations.

$$L\frac{dI_L}{dt} = V_{PV} - dV_O$$

$$C_b\frac{dV_O}{dt} = dI_L - \frac{V_O}{R_L}$$

Where d is the control signal equal to "1" when the switch is ON and "0" when the switch is OFF. Here d is the control signal equal to "1" when the switch is ON and "0" when the switch is OFF.

The control approach is to determine a control signal d that achieves a good output voltage regulation in the presence of disturbances such as step changes in load or in the source voltage, and converter parameter changes. Also, it should improve the damping and reduce the recovery time by decreasing the overshoots and undershoots.

where v_{pv} is the PV array voltage on the capacitance C_a,$i_L$and $v_b$are the current on the inductance L and the voltage on the capacitance C_b, respectively, d is the duty ratio of the pulse widthmodulated (PWM) signal to control the switching MOSFET, $R_b$and $R_L$are the internal resistances on the capacitance $C_b$and the inductance L, respectively, $V_D$is the forward voltage of the power diode, and $i_o$is a measurable load current. In addition, since the maximum power point occurs at $dP_{pv}/dv_{pv} = 0$, we take the partial derivative dP_{pv}/dv_{pv}in (5) as the control output $y(t)$, i.e.,

$$y(t) = \frac{dP_{pv}}{dv_{pv}} = i_{pv} - \frac{n_p k_{pv}}{n_s} I_{rs} v_{pv} e^{k_{pv} v_{pv}/n_s} \quad (6)$$

C. T-S Fuzzy Model

Fuzzy Logic Controller is one of the most successful applications of fuzzy set theory, introduced by Zadeh in 1965 [6]. Its major features are the use of linguistic variables rather than numerical variables. The general structure of the FLC is shown in Fig 2.

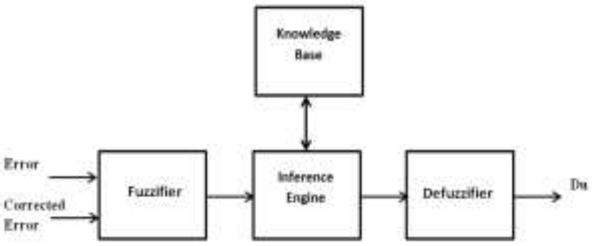


Fig. 2Structure of FLC

Now, the solar power generation system will be represented in a T-S fuzzy model. The T-S fuzzy model describes nonlinear systems by combining local linear dynamic subsystems in IF–THEN fuzzy rules.

$$\begin{bmatrix} \ddot{i_L} \\ \dot{v_O} \\ \dot{v_{pv}} \end{bmatrix} = \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & -\frac{1}{RC_b} & 0 \\ -\frac{1}{C_a} & 0 & 0 \end{bmatrix} \begin{bmatrix} i_L \\ v_O \\ v_{pv} \end{bmatrix} + \begin{bmatrix} \frac{1}{L}(V_D + v_{pv}) \\ \frac{1}{C_b} \\ \frac{1}{C_a} \end{bmatrix} d + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \left(-\frac{V_D}{L}\right) \quad (7)$$

$$\begin{bmatrix} \ddot{i_L} \\ \dot{v_O} \\ \dot{v_{pv}} \end{bmatrix} = \dot{x} = A(x)x + B(x)d + B_0 b_d \quad (8)$$

$$y = \begin{bmatrix} 0 & \left(G_a - \frac{n_p k_{pv}}{n_s} I_{rs} e^{k_{pv} v_{pv}/n_s}\right) & 0 \end{bmatrix} x = C(x)x \quad (9)$$

$$h = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} x = Ex \quad (10)$$

where $I_b = 1 - i_o / i_L$, $G_a = i_{pv}/v_{pv}$, $b_d = -V_D/L$, the state-variable vector is defined as $x = [i_L v_{pv} v_b]^T$, and h(t) is a measurable output vector composed of the inductance current and the PV array voltage. According to the previous expression and the fuzzy modeling method [6], we have to fuzzify the matrices A(x), B(x), and C(x) by T-S fuzzy rules. By observing the functions of A(x), B(x), and C(x), the fuzzy premise variables are chosen as $z_1 = i_L$,$z_2 = v_O$, $z_3 = Ga$, $z_4 = v_{pv}$, and $z_5 = \left(\frac{n_p k_{pv}}{n_s} I_{rs} e^{k_{pv} v_{pv}/n_s}\right)$. Then, the system (8) – (10) can be represented by the following T-S fuzzy rules.

Rule i): IF z_1 (t) is F_{1i} and · · · and z_5 (t) is F_{5i}THEN
$\dot{x}(t) = A_i x(t) + B_i d(t) + B_0 b_d$
$y(t) = C_i x(t)$
$h(t) = Ex(t)$, $i = 1, 2, \ldots, r$ (11)

WhereF_{ji}($j = 1, 2, \ldots, 5$) are the fuzzy sets, r is the numberof fuzzy rules, and A_i, B_i, C_i, and E are appropriate subsystemmatrices. By using the singleton fuzzifier, product fuzzy inference,and weighted average defuzzifier, the inferred output ofthe fuzzy system is,

$$x(\dot{t}) = \sum_{i=1}^{r} \mu_i(z(t))\, A_i(x)x(t) + B_i(x)d(t) + B_0 b_d$$

$$y(t) = \sum_{i=1}^{r} \mu_i(z(t))\, C_i(x)x(t)$$

$$h(t) = Ex(t) \qquad (12)$$

III. T-S FUZZY DMPPT CONTROL

To achieve the MPPT control, we have to drive the control output $y(t) = dP_{pv}/dv_{pv}$ to zero. When the control output $y(t)$ equals zero, the system achieves the maximum power operational point (x_d, u_d), which satisfies $y(t) = \sum_{i=1}^{r} \mu_i\big(z(t)\big)\, C_i(x)x(t) = 0$ and $x(\dot{t}) = \sum_{i=1}^{r} \mu_i\big(Z_d(t)\big)\, A_i(x)x(t) + B_i(x)d(t) + B_0 b_d = 0$, where $z_d$is composed of the corresponding x_d.Since the maximum power operational point is difficult to finddue to the varying atmosphere, a fuzzy DMPPT controller isintroduced in the following.First, due to the fact that only partial states are availablein measurement, the following fuzzy observer is designed tocomplete the state feedback.

Observer Rule i)

IF z_1 (t) is $F_{1i}$and · · · and z_5 (t) is F_{5i} THEN

$$\hat{x}(t) = \sum_{i=1}^{r} \mu_i(z(t))\{A_i\hat{x}(t) + B_i u(t) + B_0 b_d$$
$$+ L_i\left(h(t) - \hat{h}(t)\right) + L_i(h(t) - \hat{h}(t))\}$$
$$\hat{h}(t) = E\hat{h}(t) \qquad (13)$$

where$\hat{x}(t)$is the estimated state vector, $\hat{h}(t)$is the estimatedoutput, and $L_i$is an observer gain that is determined later. Thefuzzy inferred output is given in the above equation (15). And let us define an estimated error $\tilde{x}(t)$= $x(t)$ − $\hat{x}(t)$; then, wecan find the estimation error dynamics as follows:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r} \mu_i\big(z(t)\big)\,(A_i - L_i E)\tilde{x}(t) \qquad (14)$$

Obviously, the estimation error asymptotically converges to zeroonce $L_i$is designed such that $\sum_{i=1}^{r} \mu_i\big(z(t)\big)\,(A_i - L_i E)\tilde{x}(t)$is astable matrix.

Next, based on the fuzzy observer (13), the T-S fuzzy DMPPTcontroller is set as follows.

Controller Rule i)

IF z_1 (t) is F_{1i} and · · · and z_5 (t) is F_{5i}THEN

$$\dot{x_y}(t) = k_y y(t)$$

$$d(t) = \{K_{1i}\hat{x}(t) + K_{2i}x_y(t)\}\,, \qquad i=1,2,\ldots\ldots\ldots r$$

(15)

where$x_y(t)$ $\in R_p$is an integral state variable, ky>0, and $K_{1i}$and $K_{2i}$are control gains. The fuzzy inferred controller is obtainedas follows:

$$\dot{x_y}(t) = k_y \sum_{i=1}^{r} \mu_i\big(z(t)\big)\, C_i x(t)$$

$$d(t) = \sum_{i=1}^{r} \mu_i\big(z(t)\big)\,\{K_{1i}\hat{x}(t) + K_{2i}x_y(t)\}$$

(16)

IV. NUMERICAL SIMULATION

To verify the theoretical derivations, we carry out the fuzzyDMPPT control for a solar power generation system. Here,we use a Siemens solar PV module SP75, whose specificationsare stated in Table III. The buck converter is composedof an IRFP460 power MOSFET, 1.5mH storage inductance,47μF capacitance $C_a$and C_b, and a power rectifier diodeMBR2045CT. The internal resistances $R_b$and $R_L$of capacitance$C_b$and inductance L are 162 mΩ and 1 Ω, respectively.The forward voltage of the power rectifier diode is V_D=0.57V. The operational frequency of the converter is set to50KHz.According to the fuzzy modeling (11) and assuming theworkspace to be Ω_x= {(i_L, v_{pv}, v_b, i_o, T)| −5 ≤ i_L≤ 5, 8 ≤ v_{pv}≤ 22, 2 ≤ v_b≤ 22, 0.8i_L≤ i_o≤ 0.9i_L, 288.18 K ≤ T ≤ 363.18 K}.

V. EXPERIMENTAL RESULTS

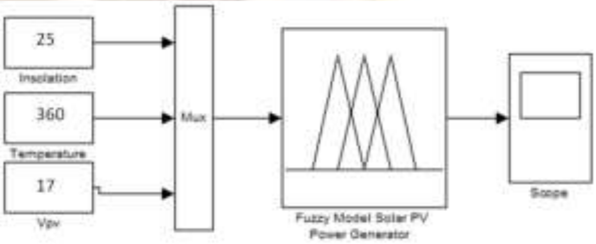


Fig. 3 Fuzzy Models Solar PV Power Generator.

The above fig. 3 shows the fuzzy model of solar power generation system, developed in MATLAB Simulink. To further verify the validity of the proposed scheme, severalexperiments of PV MPPT control are performed in this section.In our experiments, the developed controller is realized by aDSP-based control card (dSPACE DS1104), which takes theTMS320F240 DSP as the main control core. The PV voltage,PV current, inductance current, and load current are sampled bythe A/D converters and fed into the DSP card. After the controleffort is calculated from the feedback, the DS1104 card directlygenerates a PWMsignal to control the switching MOSFET. Thefrequency of the PWM signal is set to 50 KHz. In addition,the MATLAB Simulink Toolbox and Real-Time Workshop aretaken as an interface between software and hardware. Whenthe controller block is established by Simulink, the Real-TimeWorkshop plays the role of a compiler to transform the controllerinto a C code, which is downloaded to the DSP card. Then, theDS1104 is connected to the buck converter to achieve a closedloopcontrol.

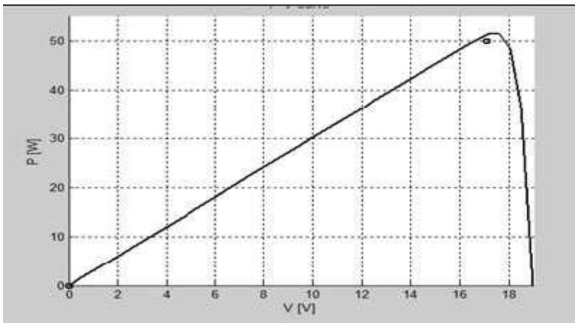
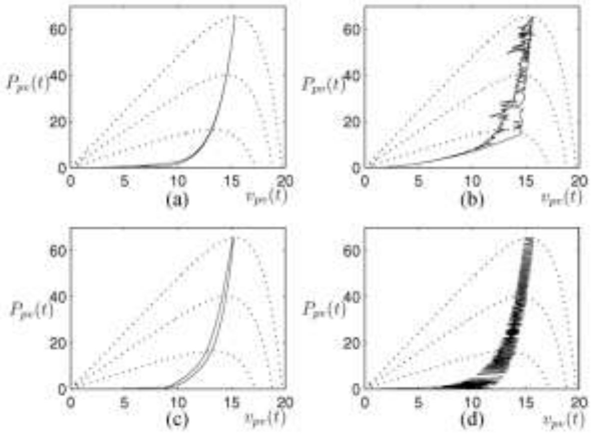


Fig.4 PV array characteristics with MPPT



(a) (b) (c) (d)

Fig. 5 P–*V* diagram of the controlled solar power generation system via (a) T-S fuzzy DMPPT control; (b) fuzzy logic control; (c) neural network control; and (d) PI control.

The fig.5 shows the comparative study of various Maximum power point tracking control of solar power generation systems and the fig.6 shows the maximum power tracked by basic PI and fuzzy model.

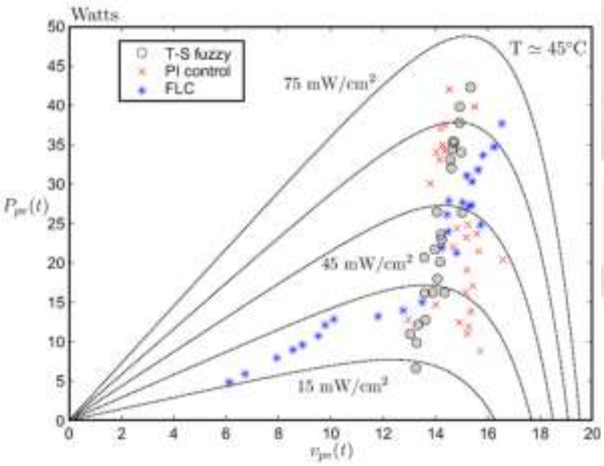


Fig. 6 Experimental *P*–*V* diagram of the controlled solar power generation system via the (o) T-S fuzzy DMPPT control, (*) fuzzy logic control, and (×) PI control.

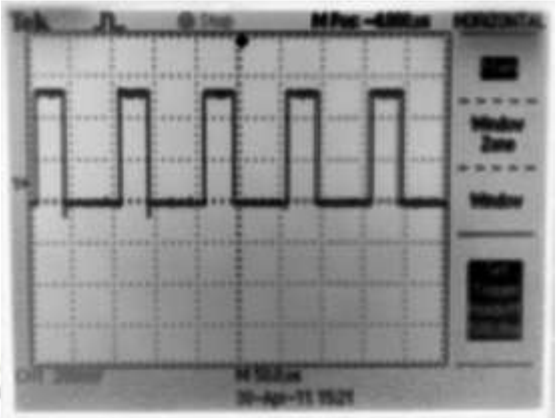


Fig. 7 Experimental Gate Pulse generated by Fuzzy.

Fig 7 shows the experimental gate pulse via the dSPACE by using T-S Fuzzy controller whichcontrols the boost converter.

VI. CONCLUSION

This paper has proposed the T-S fuzzy DMPPT controlmethod for solar power generation systems. The exact MPPT isachieved even when we consider varying atmosphere and partialstate feedback, and when the maximum power point is notcalculated. In the presence of the disturbance and uncertainty,the robust MPPT is also assured while the maximum powertracking error is attenuated to a prescribed level. Different fromtraditional MPPT methods, the proposed fuzzy DMPPT methoddoes not require the maximum power point to be calculatedunder varying atmosphere. Furthermore, the proposed methodcan draw more power than traditional methods (because traditionalmethods will lead to power chattering phenomenon orapproximate MPPT). In addition, the proposed controller hasa strict stability and performance analysis, which is not providedin traditional works. Finally, the expected performanceshave been shown by the experiments in an easy implementationform.

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