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Design of MPPT by Using Interval Type-2 T-S Fuzzy Controller

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***Abstract*—This paper proposes a maximum power point tracker (MPPT) which can accommodate widely output voltage range of solar panel under various environmental conditions. The controller in the MPPT employs the interval type-2 Takagi-Sugeno (IT2 TS) fuzzy technology. The main advantage of the proposed IT2 TS fuzzy controller is that it can handle the uncertainties in the modeling process. The experimental results are implemented to demonstrate the capability of IT2 TS fuzzy controller compared to type-1 T-S fuzzy controller.**

Keywords—MPPT; interval type-2 T-S fuzzy control

I. INTRODUCTION

The relationship between output voltage and output current of the solar panel is nonlinear. It is necessary to use the maximum power point tracker (MPPT) to regulate the output power from solar panels. The most common MPPT converter is the boost converter, which can step-up the output voltage of solar panels to the demanded voltage value and then supply to dc load or utility grid. However, if the output voltage of PV panels is greater than the voltage value of dc bus, this pure boost converter would never reach the maximum power. In addition, the ascent of voltage on the dc bus may cause some damage to other converters and loads. A convert with only one function used in a MPPT seems to be inappropriate. Therefore, this paper will develop a MPPT converter with both buck and boost functions.

Most of the conventional MPPT techniques are lack of stability analysis, so they can only approximate the MPPT [1]. Besides, some conventional techniques need to know various parameters of the PV panels in advance [2]-[3]. To improve the conventional techniques, a type-1 Takagi-Sugeno (T-S) fuzzy controller is used to eliminate these drawbacks [4]. However, there are still many uncertainties in the T-S fuzzy model, like how to determine the boundary values of antecedents. Once there is any error in the modeling process, the output from T-S fuzzy controller may not performance well. To solve this problems about uncertainties, using interval type-2 T-S (IT2 TS) fuzzy controller seem to be a nice selection.

This paper proposes a MPPT converter which has both buck and boost functions. The proposed converter can process larger output voltage range of the solar panels, and ensure that solar panels will maintain the maximum power under the variation of output voltage. Moreover, the IT2 TS fuzzy controller in the MPPT converter applies the new inference method in [7] which can be solved by using the Matlab LMI toolbox.

The remainder parts in this paper are organized as follows: In Section II, the proposed converter which has both step-up and step-down functions for MPPT is presented. In Section III, the design of the interval type-2 fuzzy controller is illustrated. In Section IV, some experiments are implemented to demonstrate the capability of the proposed IT2 TS FLC used on the MPPT converter. Finally, Conclusions are drawn in Section V.

II. CIRCUIT ARCHITECTURE OF MPPT

This paper proposes a circuit which combines with buck and boost functions. The buck model and boost model are introduced as follows, respectively.

A. Buck Model

When the input voltage V_{PV} is higher than the output voltage V_O, the circuit is operated on buck mode and the switch M_2 keeps turn off. The circuit operating modes include mode I (M_1: on; M_2: off) and mode II (M_1: off; M_2: off). The proposed circuit in buck mode is shown in Fig. 1.

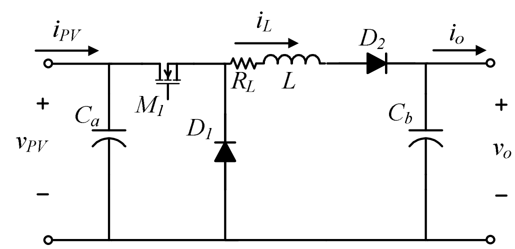

Fig. 1. The proposed circuit in buck mode.

B. Boost Model

When the input voltage V_{PV} is lower than the output voltage V_O, the circuit is operated in boost mode and the switch M_1

keeps turn on. The circuit operating modes include mode III (M_1: on; M_2: on) and mode IV (M_1: on; M_2: off). The proposed circuit in boost mode is shown in Fig. 2.

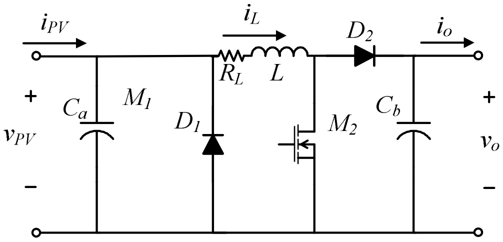

Fig. 2. The proposed circuit in boost mode.

III. IT2 TS FLC

In order to implement the IT2 TS FLC, the details of converter models, rule tables and membership functions are all described in the following sections.

A. Buck Converter Model

First, by taking the derivative of input power P from PV panel at output voltage V_{PV} from PV panel, we can obtain equation (1):

$$\begin{aligned}\frac{dP}{dV_{PV}} &= I_{PV} + V_{PV}\frac{dI_{PV}}{dV_{PV}} \\ &= I_{PV} - \frac{n_q q}{kTAn_s} I_{sat} V_{PV} \exp\left(\frac{qV_{PV}}{kTAn_s}\right)\end{aligned} \tag{1}$$

When any operating point satisfies the condition dP/dV_{PV} = 0, it is the maximum power point and also the target of this paper. Therefore we select equation (1) to be the control output. According to Fig. 1, we can express this system with the dynamic equations (2), (3) and (4):

$$i_L = \frac{1}{L}\left(-R_L i_L - V_O + \left(V_D + V_{PV}\right)u - 2V_D\right) \tag{2}$$

$$\dot{V}_{PV} = \frac{1}{C_a}\left(i_{PV} - i_L u\right) \tag{3}$$

$$\dot{V}_O = \frac{1}{C_b}\left(i_L - i_O\right) \tag{4}$$

where u is the duty ratio of switch M_1. Then we can rewrite the equations (2), (3) and (4) as equation (5), and equation (1) as equation (6):

$$\begin{aligned}\begin{bmatrix} \dot{i}_L \\ \dot{v}_{PV} \\ \dot{v}_O \end{bmatrix} &= \begin{bmatrix} -\frac{1}{L}R_L & 0 & -\frac{1}{L} \\ 0 & \frac{1}{C_a}G_a & 0 \\ \frac{1}{C_b}I_b & 0 & 0 \end{bmatrix}\begin{bmatrix} i_L \\ v_{PV} \\ v_O \end{bmatrix} + \begin{bmatrix} \frac{1}{L}\left(V_D + v_{PV}\right) \\ -\frac{1}{C_a}i_L \\ 0 \end{bmatrix}u + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}\left(-\frac{2V_D}{L}\right) \\ &\equiv A(x)x + B(x)u + H\sigma\end{aligned} \tag{5}$$

$$\begin{aligned}y(t) &= \begin{bmatrix} 0 & G_a - \frac{n_P}{n_s}\frac{q}{kTA}I_{rs}\left[\exp\left(\frac{q}{kTA}\frac{V_{PV}}{n_s}\right)\right] & 0 \end{bmatrix}\begin{bmatrix} i_L \\ v_{PV} \\ v_O \end{bmatrix} \\ &\equiv C(x)x\end{aligned} \tag{6}$$

where $I_b = 1 - i_o/i_L$, $G_a = i_{PV}/V_{pv}$, $b_d = -2V_D/L$, $x = [\ i_L\ V_{PV}\ V_o\ ]^T$. And by the T-S fuzzy modeling, we let the premises to be $z_1 = G_a$, $z_2 = V_{PV}$, $z_3 = i_L$, $z_4 = I_{PV} - dP/dV_{PV}$. Thus, the equations (5) and (6) can be represented by following fuzzy rules:

Rule i:

IF $z_1(t)$ *is* M_{1i} *and ... and* $z_4(t)$ *is* M_{4i}

THEN

$$\begin{aligned}&\dot{x}(t) = A_i x(t) + B_i u(t) + H\sigma \\ &y(t) = C_i x(t) \\ &i = 1,2,..., r\end{aligned} \tag{7}$$

where M_{ji} (j = 1,2,...,4) is the fuzzy set, r is the number of fuzzy rules, A_i , B_i and C_i are the matrices of the subsystem in each rule. Then multiplying the weight of each rule, we can derive the fuzzy system as equation (8):

$$\begin{aligned}\dot{x}(t) &= \sum_{i=1}^{r} h_i\left(z(t)\right)\left\{A_i x(t) + B_i u(t) + H\sigma\right\} \\ y(t) &= \sum_{i=1}^{r} h_i\left(z(t)\right)C_i x(t)\end{aligned} \tag{8}$$

where $h_i(z(t))$ is the weight of each rule after normalization. And the weight of each rule is computed by substituting into the membership function, which is constructed by the maximum and minimum value of each premise. From equations (5) and (6), we can rewrite A_i, B_i and C_i as equations (9), (10) and (11):

$$A_i = \begin{bmatrix} -\frac{1}{L}R_L & 0 & -\frac{1}{L} \\ 0 & \frac{1}{C_a}\theta_{3i} & 0 \\ \frac{1}{C_b}I_b & 0 & 0 \end{bmatrix} \tag{9}$$

$$B_i = \begin{bmatrix} -\frac{1}{L}\left(V_D + \theta_{2i}\right) \\ -\frac{1}{C_a}\theta_{1i} \\ 0 \end{bmatrix} \tag{10}$$

$$C_i = \begin{bmatrix} 0 & \theta_{4i} & 0 \end{bmatrix} \tag{11}$$

B. Boost Converter Model

Likewise, we can get the state equations, i.e. (12), (13) and (14), from the operating principle:

$$i_L = \frac{1}{L}\left(-R_L i_L + V_{PV} - V_O + \left(V_D + V_{PV}\right)u - V_D\right) \tag{12}$$

$$\dot{V}_{PV} = \frac{1}{C_a}\left(i_{PV} - i_L\right) \tag{13}$$

$$\dot{V}_O = \frac{1}{C_b}\left(i_L - i_O - i_L u\right) \tag{14}$$

As the same as the buck converter, we can rewrite equations (12), (13) and (14) as matrix form (15), and equation (7) as equation (16) according to Fig. 2:

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_{PV} \\ \dot{v}_O \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}R_L & \frac{1}{L} & -\frac{1}{L} \\ -\frac{1}{C_a} & \frac{1}{C_a}G_a & 0 \\ \frac{1}{C_b}I_b & 0 & 0 \end{bmatrix} \begin{bmatrix} i_L \\ v_{PV} \\ v_O \end{bmatrix} + \begin{bmatrix} \frac{1}{L}(V_D + V_O) \\ 0 \\ -\frac{1}{C_b}i_L \end{bmatrix} u + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \left(-\frac{V_D}{L} \right)$$

$$\equiv A(x)x + B(x)u + H\sigma \tag{15}$$

$$y(t) = \begin{bmatrix} 0 & G_a - \frac{n_P}{n_s}\frac{q}{kTA} I_{rs}\left[\exp\left(\frac{q}{kTA}\frac{V_{PV}}{n_s} \right) \right] & 0 \end{bmatrix} \begin{bmatrix} i_L \\ v_{PV} \\ v_O \end{bmatrix}$$

$$\equiv C(x)x \tag{16}$$

where $I_b = 1 - i_o/i_L$, $G_a = i_{PV}/V_{pv}$, $\sigma = -V_D/L$, $x = [\, i_L \; V_{PV} \; V_o \,]^T$. Likewise, by using the T-S fuzzy modeling, we let the premises, z_i, to be $z_1 = G_a$, $z_2 = I_b$, $z_3 = i_L$, $z_4 = I_{PV} - dP/dV_{PV}$. From equations (15) and (16), we can rewrite A_i, B_i and C_i as equations (17), (18) and (19):

$$A_i = \begin{bmatrix} -\frac{1}{L}R_L & \frac{1}{L} & -\frac{1}{L} \\ -\frac{1}{C_a} & \frac{1}{C_a}\theta_{3i} & 0 \\ \frac{1}{C_b}\theta_{2i} & 0 & 0 \end{bmatrix} \tag{17}$$

$$B_i = \begin{bmatrix} \frac{1}{L}(V_D + V_O) \\ 0 \\ -\frac{1}{C_a}\theta_{1i} \end{bmatrix} \tag{18}$$

$$C_i = \begin{bmatrix} 0 & \theta_{4i} & 0 \end{bmatrix} \tag{19}$$

C. *Antecedents and Rules*

The membership function of four premises is showed in Fig. 3. In order to simplification, we rewrite the memberships function as equation (20):

$$M_{aj} = \frac{-d_j}{D_j + d_j} + \left(\frac{1}{D_j + d_j} \right) z_j(t) \tag{20}$$
$$M_{bj} = 1 - M_{aj}$$

where D_j and d_j is the maximum and minimum value of $z_j(t)$ respectively.

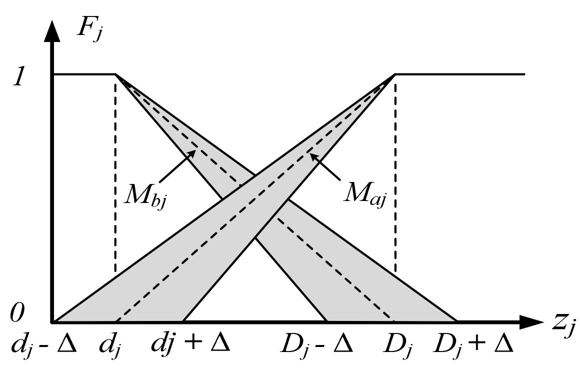

Fig. 3. The membership function of z_j.

D. *Controller Design*

After the boundary values of each operating mode are set, the controller can be designed as equation (21):

Rule i:

IF $z_1(t)$ *is* $\widetilde{M}_{1i}$ *and ... and* $z_4(t)$ *is* $\widetilde{M}_{4i}$

THEN

$$\begin{aligned} u(t) &= F_{1i}x(t) + F_{2i}\xi(t) \\ \dot{\xi}(t) &= y(t) \\ i &= 1,2,\ldots, r \end{aligned} \tag{21}$$

where ξ is a variable of the integral state. F_{1i} and F_{2i} is the control gain which is obtained by the pole-placement method.

By using the new inference method from [7], we can obtain the following equations:

$$\dot{\xi} = \frac{m\sum_{i=1}^{r} \overline{w}_i(z(t))C_i x(t)}{\sum_{i=1}^{r} \overline{w}_i} + \frac{n\sum_{i=1}^{r} \underline{w}_i(z(t))C_i x(t)}{\sum_{i=1}^{r} \underline{w}_i} \tag{22}$$

$$u(t) = \frac{m\sum_{i=1}^{r} \overline{w}_i(z(t))\left[F_{1i}x(t) + F_{2i}\xi(t)\right]}{\sum_{i=1}^{r} \overline{w}_i} + \frac{n\sum_{i=1}^{r} \underline{w}_i(z(t))\left[F_{1i}x(t) + F_{2i}\xi(t)\right]}{\sum_{i=1}^{r} \underline{w}_i} \tag{23}$$

where

$$\begin{aligned} \overline{w}_i &= \overline{\mu}_{\widetilde{M}_{1i}}(z_1(t)) \times \overline{\mu}_{\widetilde{M}_{2i}}(z_2(t)) \times \overline{\mu}_{\widetilde{M}_{3i}}(z_3(t)) \times \overline{\mu}_{\widetilde{M}_{4i}}(z_4(t)) \\ \underline{w}_i &= \underline{\mu}_{\widetilde{M}_{1i}}(z_1(t)) \times \underline{\mu}_{\widetilde{M}_{2i}}(z_2(t)) \times \underline{\mu}_{\widetilde{M}_{3i}}(z_3(t)) \times \underline{\mu}_{\widetilde{M}_{4i}}(z_4(t)) \end{aligned} \tag{24}$$

Then by substituting the equation (22) and (23) into equation (21) and changing a new pole $s(t) = [x^T(t) \;\; \xi^T(t)]^T$, we can obtain the equation (25):

$$\begin{aligned} \dot{s}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r}\sum_{k=1}^{r} h_i(z(t))\overline{w}_j(z(t))\underline{w}_k(z(t)) \\ \times \left\{ mA_{ijk}s(t) + nA_{ijk}s(t) + \overline{H}\sigma \right\} \end{aligned} \tag{25}$$

where

$$h_i = \frac{\mu_{M_{1i}}(z_1(t)) \times \mu_{M_{2i}}(z_2(t)) \times \mu_{M_{3i}}(z_3(t)) \times \mu_{M_{4i}}(z_4(t))}{\sum_{i=1}^{r}\left[\mu_{M_{1i}}(z_1(t)) \times \mu_{M_{2i}}(z_2(t)) \times \mu_{M_{3i}}(z_3(t)) \times \mu_{M_{4i}}(z_4(t)) \right]} \tag{26}$$

$$A_{ijk} = \frac{1}{m+n}\begin{bmatrix} A_i + mB_iF_{1j} + nB_iF_{1k} & mB_iF_{2j} + mB_iF_{2k} \\ mC_j + nC_k & 0 \end{bmatrix} \tag{27}$$

$$\overline{H} = \begin{bmatrix} H^T \\ 0 \end{bmatrix} \tag{28}$$

E. *Stability Analysis*

To analyze the stability of the MPPT, we use the Lyapunov function $V(s) = s^TPs$, where $P = P^T > 0$, to execute stable analysis. By substituting the equation (25), we can obtain the equation (29):

$$\dot{V}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r}\sum_{k=1}^{r} h_i(z(t))\overline{w}_j(z(t))\underline{w}_k(z(t)) \times \left\{ \begin{array}{l} s^T\left[m\left(PA_{ijk} + A_{ijk}^T P\right) + n\left(PA_{ijk} + A_{ijk}^T P\right)\right]s \\ + s^T P\overline{H}\sigma + \sigma^T \overline{H}^T Ps \end{array} \right\}$$

$$\le \sum_{i=1}^{r}\sum_{j=1}^{r}\sum_{k=1}^{r} h_i(z(t))\overline{w}_j(z(t))\underline{w}_k(z(t)) \times s^T \begin{bmatrix} m\left(PA_{ijk} + A_{ijk}^T P\right) \\ + n\left(PA_{ijk} + A_{ijk}^T P\right) \\ + P\overline{H}\overline{H}^T P \end{bmatrix} s + \sigma^T\sigma \tag{29}$$

From the above inequality, we can get the following equation:

$$m\left(PA_{ijk} + A_{ijk}^T P\right) + n\left(PA_{ijk} + A_{ijk}^T P\right) + P\overline{HH}^T P + S < 0 \tag{30}$$

where $S = S^T > 0$.

By the Schur complement, we get the stability conditions in LMI form:

$$\begin{bmatrix} m\left(A_{ijk}X + XA_{ijk}^T\right) + n\left(A_{ijk}X + XA_{ijk}^T\right) + \overline{HH}^T & X \\ X & -S \end{bmatrix} < 0 \tag{31}$$

IV. Experimental Results

A. Buck Mode

Fig. 4 shows the waveforms of voltage and current in the atmospheric conditions of 25°*C* and 1000 W/m^2 by using type-1 T-S fuzzy method in the buck mode. The yellow and green line is the voltage and current from PV panel respectively. The purple line is the voltage from dc bus. The precision of the type-1 T-S fuzzy method is depicted in the Fig. 5. By using this method, the MPPT tracking rate can reaches about 98.667%.

Fig. 6 shows the waveforms of voltage and current in the atmospheric conditions of 25°*C* and 1000 W/m^2 by using Interval type-2 T-S fuzzy method in the buck mode. The yellow and green line is the voltage and current from PV panel respectively. The purple line is the voltage from dc bus. The precision of the Interval type-2 T-S fuzzy method is depicted in the Fig. 7. By using this method, the MPPT tracking rate can be improved to 99.76%.

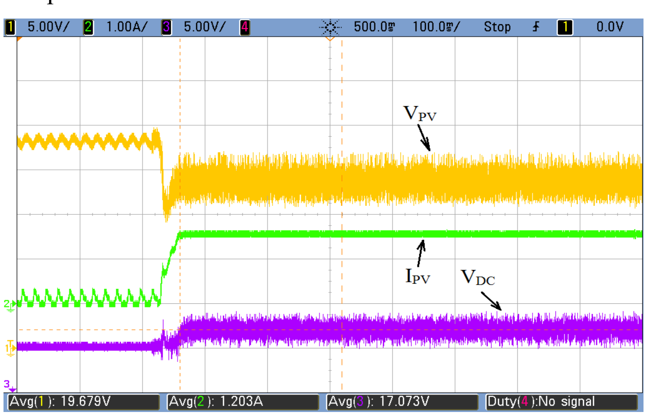

Fig. 4. Waveforms in buck mode by using type-1 T-S fuzzy.

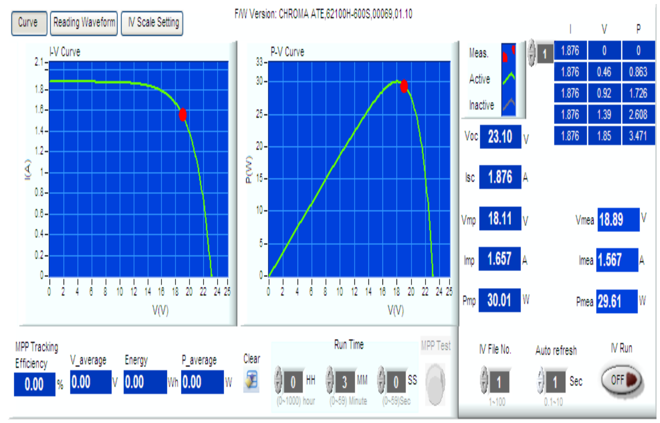

Fig. 5. MPPT tracking rate in boost mode by using T1 TS.

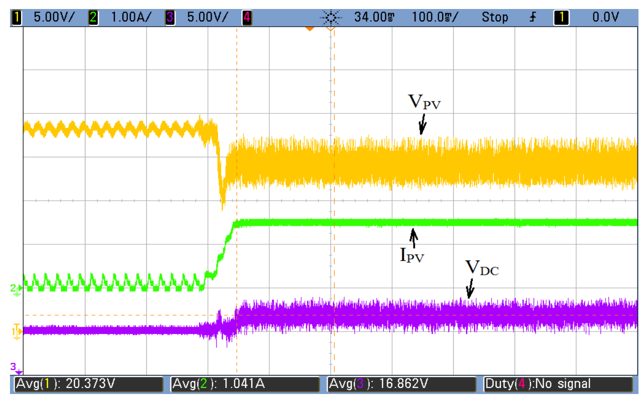

Fig. 6. Waveforms in boost mode by using IT2 TS.

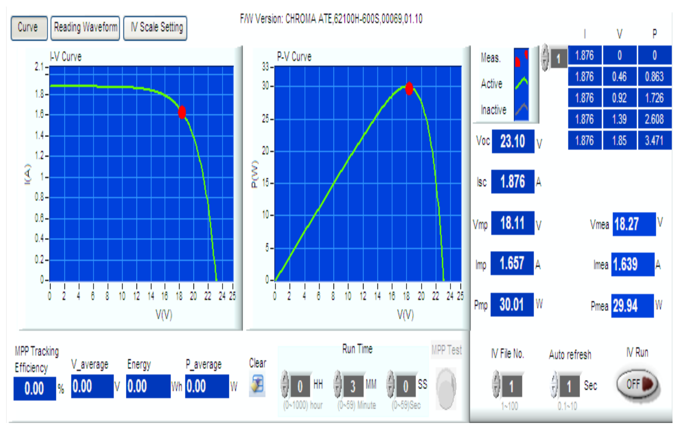

Fig. 7. MPPT tracking rate in boost mode by using IT2 TS.

B. Boost Mode

Fig. 8 shows the waveforms of voltage and current in the atmospheric conditions of 25°*C* and 1000 W/m^2 by using type-1 T-S fuzzy method in the boost mode. The yellow and green line is the voltage and current from PV panel respectively. The purple line is the voltage from dc bus. The precision of the type-1 T-S fuzzy method is depicted in the Fig. 9. By using this method, the MPPT tracking rate can reaches about 98.63%.

Fig. 10 shows the waveforms of voltage and current in the atmospheric conditions of 25°*C* and 1000 W/m^2 by using Interval type-2 T-S fuzzy method in the boost mode. The yellow and green line is the voltage and current from PV panel respectively. The purple line is the voltage from dc bus. The precision of the IT2 TS fuzzy method is depicted in the Fig. 11. By using this method, the MPPT tracking rate can be improved to 99.60%. These results show that using IT2 TS will improve the tracking efficiency if the design model is influenced by some uncertainties.

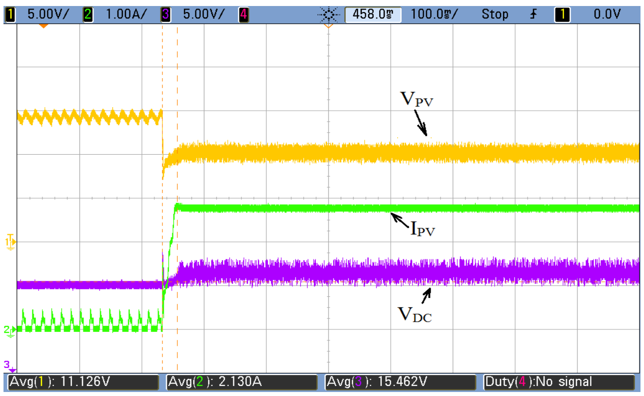

Fig. 8. Waveforms in boost mode by using T1 TS..

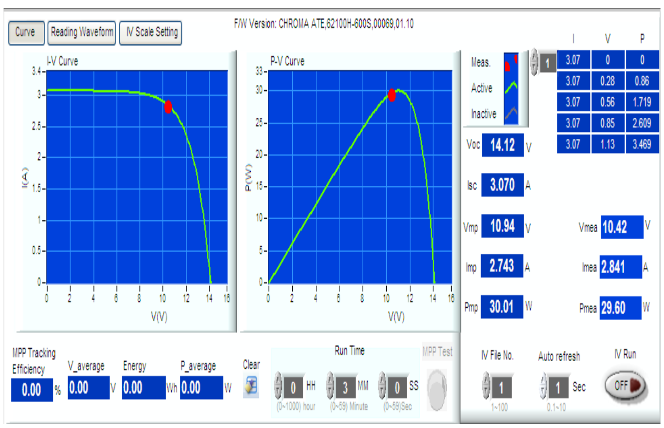

Fig. 9. MPPT tracking rate in boost mode by using T1 TS.

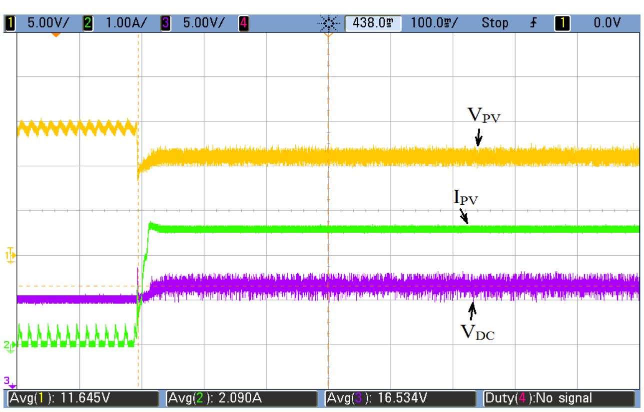

Fig. 10. Waveforms in boost mode by using IT2 TS.

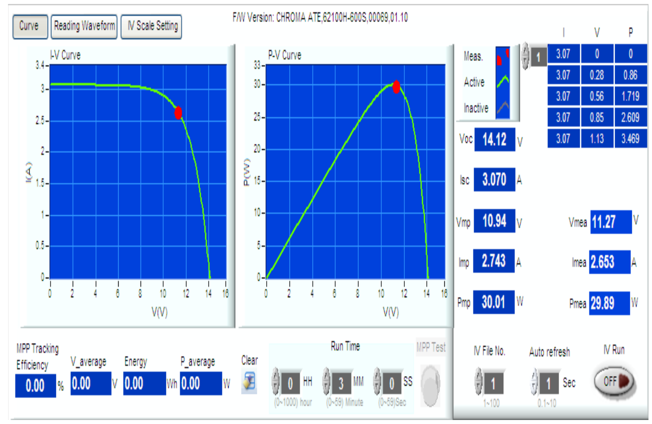

Fig. 11. MPPT tracking rate in boost mode by using IT2 TS.

V. Conclusion

This paper presented the applications of type-1 and type-2 T-S fuzzy control on a MPPT converter which combines with buck and boost functions. The experimental results demonstrate that using IT2 TS can improve the efficiency of the MPPT tracking rate when the original model is affected by some uncertainties. This method is applicable in both buck mode and boost mode.

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