A New Digital Double Integral Sliding Mode Maximum Power Point Tracker for Photovoltaic Power Generation Application

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***Abstract*— This paper proposed a new digital double integral sliding mode controller based MPPT (DDISMC-MPPT) for tracking the maximum power point (MPP) of a photovoltaic (PV) panel. In this DDISMC-MPPT, a new double integral sliding surface has been chosen and with PWM mechanism its operation is enhanced with fixed switching frequency. The DDISMC-MPPT controller is designed considering the reaching and stability conditions. It is found that the proposed controller inherent robustness and is stable. Comparing with two available DDISMC-MPPTs such as Tan's [6] and Jiao's [7] DDISMCs, this proposed DDISMC-MPPT performs better MPP tracking with less chattering. It is also confirmed that the settling time and chattering yielded in the proposed controller are less compared to that of Tan's and Jiao's DDISMC-MPPTs.**

***Index Terms*—PV system, MPPT, SMC, Proposed DISMC-MPPT, Tan's DISMC-MPPT, Jiao's DISMC-MPPT.**

I. INTRODUCTION

PV systems need to be operated at their MPPs to achieve higher efficiency of energy conversion. To track the MPP, a maximum power point tracker (MPPT) is to be placed between the PV panel and load. Maximum power point tracking is an important aspect in a PV system because at MPP, a PV panel operates most efficiently as it delivers the maximum power.

A number of MPPT techniques are reported in literature [1-3]. Among them, perturb and observe (P&O) and incremental conductance (IC) techniques are straight forward, accurate and easy to apply, hence commonly used. But, both these techniques do not perform well in rapidly changing environmental conditions [4]. SMC is suitable for MPP tracking of a PV system in rapidly changing environmental conditions [5] because SMC possesses inherent robustness, stability. In addition to that, it has high degree of flexibility in design choices and also easy to implement using DSP, microcontroller, FPGA, etc. But, conventional HM based SMC has two major drawbacks, such as the variable operating frequency of SMC and presence of high frequency chattering. To tackle the variable operating frequency problem, a PWM based indirect sliding mode controller and for the high frequency chattering problem, an integral term has been added to the sliding surface. This controller with an integral term is called integral sliding mode controller (ISMC) [6]. To further improve the response, another integral term can be supplemented which is usually referred to as a double integral sliding mode controller (DISMC) [7]. On introducing the double integral of error term in sliding surface of DISMC exhibits fast dynamic responses for a wide range of operating conditions. It also inherent the robustness and stability features of SMC. There exist a number of DISMC with different sliding surfaces [8-10]. Out of which Tan's [7] and Jiao's [10] are distinctly applied in output voltage regulation of converters.

Performance of a DISMC design greatly depends on selection of an appropriate sliding surface because accuracy and response time of the controlled system is dependent on the sliding surface. In this paper, DISMC with a new double integral sliding surface has been designed and applied for MPP tracking of a PV system.

II. PROBLEM FORMULATION

Fig.1 describes a simple topology of a stand-alone PV system. It consists of a PV panel, a DC/DC converter, a load and a control circuit to control the switching operation of DC/DC converter. The control circuit has a DDISMC-MPPT so that the power output from PV panel is always the maximum.

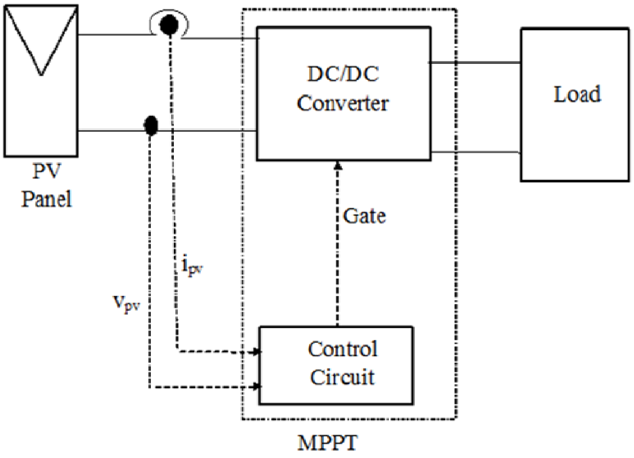


Fig. 1 A stand-alone PV system topology with DDISMC-MPPT

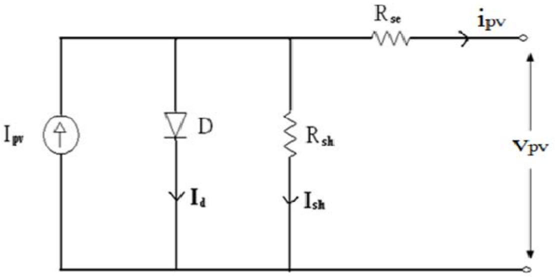


Fig. 2 Equivalent circuit model of a PV panel

The equivalent circuit of PV panel is shown in Fig.2. In the circuit, the expression for PV panel output current (i_{pv}) can be represented as follows.

$$i_{pv} = I_{pv} - I_o\left[\exp\left(\frac{v_{pv}+i_{pv}R_{se}}{N_sV_t}\right)-1\right]-\frac{v_{pv}+i_{pv}R_{se}}{R_{sh}} \tag{1}$$

where v_{pv} is the output voltage of the PV panel. I_{pv}, I_0, V_t, N_s, R_{se}, and R_{sh} are photo-generated current, dark-saturation current, thermal voltage, number of series cells a in PV panel, series resistance and shunt resistance respectively. The nonlinear model of a DC/DC boost converter system is given by

$$\left.\begin{aligned} \dot{i}_L &= \frac{v_{pv}}{L}-\frac{v_o}{L}+\frac{v_o}{L}u \\ \dot{v}_{pv} &= \frac{1}{C_1 r_{pv}}v_{pv}-\frac{1}{C_1}i_L+\frac{1}{C_1}i_L u \\ y &= v_{pv} \end{aligned}\right\} \tag{2}$$

where i_L, v_{pv}, v_o and r_{pv} are the inductor current, PV panel voltage, load voltage and dynamic resistance of PV panel respectively. C_1 and L are the input capacitor and inductor of the DC/DC boost converter respectively. Since, v_o is dependent on v_{pv} and i_L, hence eq (2) can be written as

$$\dot{X} = f\left(X\right)+g\left(X\right)u \tag{3}$$

where,

$$\left.\begin{aligned} X &= \begin{bmatrix} i_L & v_{pv} \end{bmatrix}^T \\ f\left(X\right) &= \begin{bmatrix} \frac{v_{pv}}{L}-\frac{v_o}{L} & \frac{1}{C_1 r_{pv}}v_{pv}+\frac{1}{C_1}i_L \end{bmatrix} \\ g\left(X\right) &= \begin{bmatrix} -\frac{v_o}{L} & \frac{i_L}{C_1} \end{bmatrix} \end{aligned}\right\} \tag{4}$$

III. DESIGN OF THE PROPOSED DISMC-MPPT

For a DC/DC converter, the switching function u is the duty-ratio and $0 \le u \le 1$. The proposed DISMC-MPPT has the PWM-based switching function u such that it has only two logic-states 0. Referring to Fig.2, this switching function adopts the following switching law.

$$u = \frac{1}{2}\left[1+\operatorname{sgn}\left(S\right)\right] \tag{5}$$

where S is the proposed sliding surface and defined as

$$S = a_1e_1 + a_2e_2 + a_3e_3 + a_4e_4 \tag{6}$$

The terms a_1, a_2, a_3, a_4 denote the sliding coefficients and the e_1, e_2, e_3, e_4 are various error signals and are defined as follows.

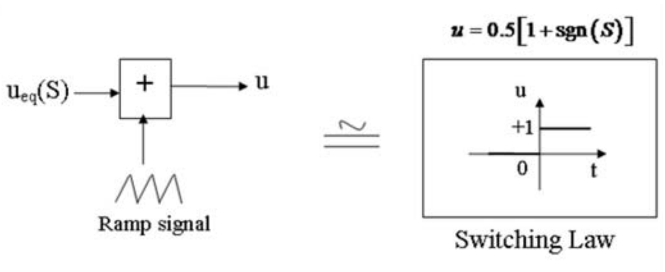


Fig.2. Switching Control Law

$$\left.\begin{aligned} e_1 &= i_{ref} - i_L \\ e_2 &= V_{ref} - \beta v_{pv} \\ e_3 &= \int\left(V_{ref}-\beta v_{pv}\right)dt \\ e_4 &= \int\left[\int\left(V_{ref}-\beta v_{pv}\right)dt\right]dt \end{aligned}\right\} \tag{7}$$

$$i_{ref} = \alpha\left(V_{ref}-\beta v_{pv}\right) \tag{8}$$

Differentiating the above state variables leads to

$$\left.\begin{aligned} \dot{e}_1 &= \frac{d}{dt}\left[i_{ref}-i_L\right] = -\frac{\beta K}{C_1}i_c - \frac{v_{pv}}{L}-\frac{v_o}{L}+\frac{v_o}{L}u \\ \dot{e}_2 &= \frac{d}{dt}\left[V_{ref}-\beta v_{pv}\right] = -\frac{\beta}{C_1}i_c \\ \dot{e}_3 &= V_{ref}-\beta v_{pv} \\ \dot{e}_4 &= \int\left[V_{ref}-\beta v_{pv}\right]dt \end{aligned}\right\} \tag{9}$$

Taking derivative of S gives

$$\dot{S} = a_1\dot{e}_1 + a_2\dot{e}_2 + a_3\dot{e}_3 + a_4\dot{e}_4 \tag{10}$$

Applying eq (9) in eq (10), u_{eq} is obtained as follows.

$$u_{eq} = 1 - K_1\frac{i_c}{v_o} - \frac{v_{pv}}{v_o} + K_2\frac{e_2}{v_o} + K_3\frac{e_3}{v_o} \tag{11}$$

where

$$\begin{aligned} K_1 &= \frac{\beta L}{a_1}\left(\frac{a_1K + a_2}{C_1}\right) \\ K_2 &= \frac{a_3L}{a_1} \\ K_3 &= \frac{a_4L}{a_1} \end{aligned} \tag{12}$$

Here, K_1, K_2 and K_3 are selected empirically such that existence and stability conditions should be satisfied. The structure of this DDISMC-MPPT is shown in Fig.3. In this figure, G_s is a factor multiplied with V_{ref} to make it of chip-level for ease in hard-ware implementation of the proposed controller. To further simplify the controller implementation, it is assumed that $G_s = \beta$. The basic idea behind the proposed DDISMC-MPPT is that the voltage (v_{c1}) across the capacitor C_1 is made equal to v_{pv} and current (i_c) across C_1 is reduced to zero so that the total panel output current (i_{pv}) flows through the inductor L. Thus, we have

$$\left.\begin{array}{l} v_{C1} \approx v_{pv} \\ i_C \approx 0 \\ i_L \approx i_{pv} \end{array}\right\} \qquad (13)$$

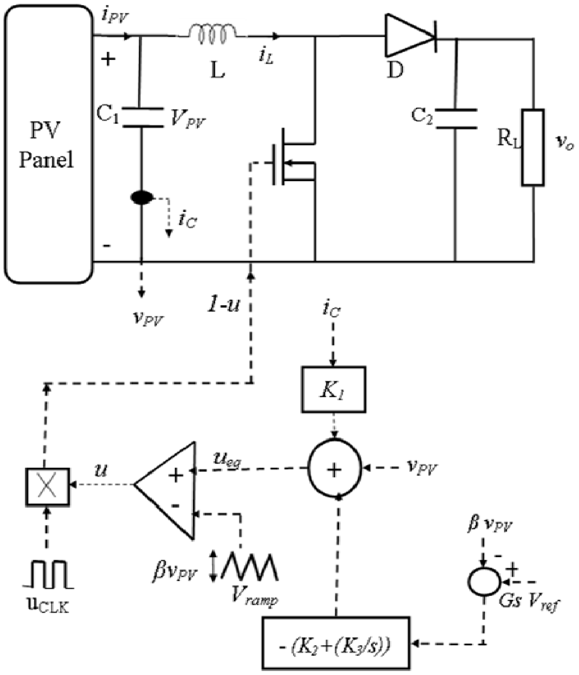


Fig.3. Structure of the proposed DDISMC-MPPT

A. Reaching Condition

We need to ensure that the state trajectory of the system should be directed always towards the sliding surface from any initial state. For this, from reaching conditions we have

$$S\dot{S} < 0 \qquad (14)$$

Referring to eq (14), if $S > 0$, then $\dot{S} < 0$ and vice-versa. Further, referring eq.s (7-11), in a boost converter the following conditions are valid. When,

$S > 0, \dot{S} < 0 \Rightarrow u = 0$

$$K_1 i_c + v_{pv} + K_2 e_2 + K_3 e_3 < 0 \qquad (15)$$

and when

$S < 0, \dot{S} > 0 \Rightarrow u = 1$

$$K_1 i_c + v_{pv} + K_2 e_2 + K_3 e_3 > 0 \qquad (16)$$

At steady state eq.s (15-16) are modified as follows.

$$K_1 i_{c(\max)} + K_2 e_{2(\max)} + K_3 e_{3(\max)} > v_{pv(\max)} \qquad (17)$$

$$K_1 i_{c(\min)} + K_2 e_{2(\min)} + K_3 e_{3(\min)} > v_{pv(\min)} \qquad (18)$$

v_{pv}, $v_{pv(min)}$, $v_{pv(max)}$, are minimum and maximum PV panel voltages respectively, $i_{c(min)}$, $v_{c(max)}$, are minimum and maximum inductor currents respectively.

B. Stability Condition

To ensure that the state trajectory remains in the sliding surface, we need to verify the stability condition of the PV system with the proposed controller. This controller has both the current and voltage state variables. Hence, the sliding motion equation cannot be solved analytically. The stability condition can be obtained analytically if the sliding motion equation is represented linearly. This is possible by first by rewriting the combined state equations of the PV system and boost converter in Laplace form as follows.

$$s^2 I_L(s) + \frac{1}{L}\left[K_1 I_L(s) I_c(s) - K_2 E_2(s)\right] s - K_3 E_2(s) = 0 \qquad (19)$$

and

$$s^2 V_{pv}(s) + \frac{1}{L} s \left[\frac{1}{C_1 r_{pv}} V_{pv}(s) - \frac{I_L(s)}{C_1} V_{pv}(s) + K_1 \frac{I_L(s) I_c(s)}{C_1} - K_2 \frac{I_L(s)}{C_1} E_2(s)\right] - K_3 E_2(s) = 0 \qquad (20)$$

Applying Routh-Hurwiz stability criterion to eq (19), we have

s^2	$I_L(s)$	$-K_3 E_2(s)$
s	$\frac{1}{L}\left[K_1 I_L(s) I_c(s) - K_2 E_2(s)\right]$	0
s^0	$K_3 E_2(s)$	0

(21)

Similarly, applying Routh-Hurwiz stability criterion to eq (20), we have

s^2	$V_{pv}(s)$	$-K_3 E_2(s)$
s	$\frac{1}{L} s \left[\begin{array}{l} \frac{1}{C_1 r_{pv}} V_{pv}(s) - \frac{I_L(s)}{C_1} V_{pv}(s) \\ +K_1 \frac{I_L(s) I_c(s)}{C_1} - K_2 \frac{I_L(s)}{C_1} E_2(s) \end{array}\right]$	0
s^0	$K_3 E_2(s)$	0

(22)

Referring to eq.s (21-22), the following condition must be satisfied for achieving stability of the PV system with the proposed controller.

$$\frac{1}{L}\left[K_1 I_L(s) I_c(s) - K_2 E_2(s)\right] > 0$$

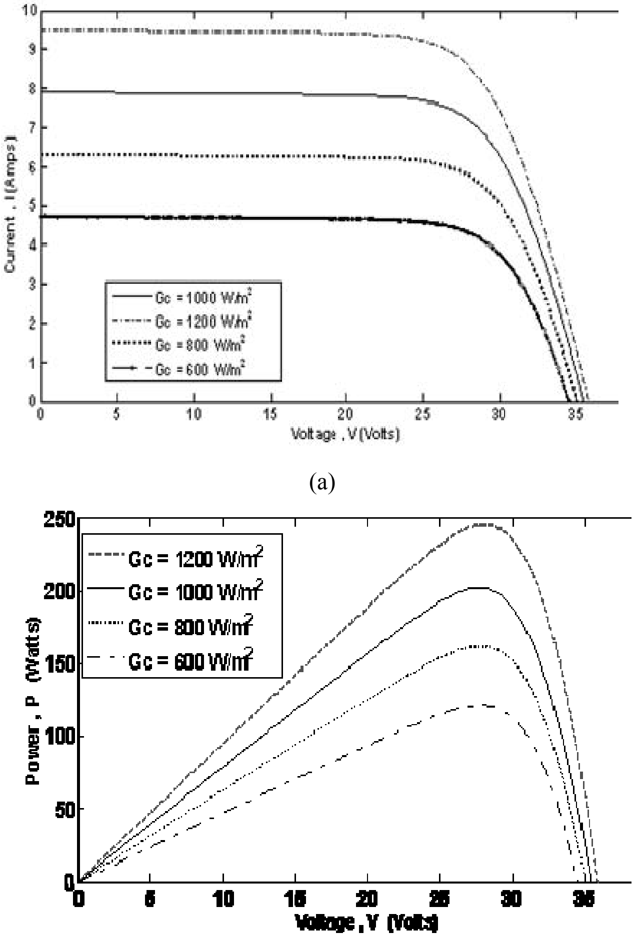
$$-K_3 E_2(s) > 0 \Rightarrow K_3 < 0 \tag{23}$$

$$\frac{1}{C_1}\left[\begin{matrix} I_L(s)V_{pv}(s) - \dfrac{V_{pv}(s)}{r_{pv}} + K_1 I_L(s) I_c(s) \\ -K_2 I_L(s) E_2(s) \end{matrix}\right] > 0$$

The above three conditions such as existence, reaching and stability conditions should be satisfied to ensure the close-loop stability of the PV system. K_1, K_2 and K_3 are selected such that eqs (15-16) and eq (23) are valid.

IV. Results and Discussions

The performance of the proposed DDISMC-MPPT was verified on a SSI-M6-205 PV system [11]. I-V and P-V characteristics of the panel are shown in Fig.4.



(a)

(b)

Fig.4 (a) P-V Characteristics, (b) I-V Characteristics of SSI-M6-205 solar panel at different solar radiations

The tracking performance of the proposed controller was evaluated and tested using MATLAB/SIMULINK. In this paper, the PV panel voltage at MPP is taken as V_{ref} of the controller and is calculated online for every change in solar irradiance or temperature using the MPPT algorithm proposed by [12]. The values of V_{ref} for different solar irradiance or temperature are listed in Table-I. For efficient tracking of the V_{ref} of the studied PV panel, the parameters of the values of different components are shown in Table-II. In this table, the values of the components of the given DC/DC boost converter i.e.; inductor (L) and capacitors (C_1 and C_2) are constant. Taking these values of L, C_1 and C_2, the parameters K_1, K_2 and K_3 are empirically chosen such that eqs (15-16 and 23) are satisfied.

Table I. Values of V_{ref} of the studied PV Panel calculated at different solar radiations

G (watts/m^2)	**V_{ref} (volts)**
250	25.99
500	27
750	27.59
1000	28.04

Table II. Values of Comparison of the proposed DDISMC with Tan's DISMC and Jiao's DDISMC-MPPT

DDISMC Components	**Values**
Load	100 Ω
L	18 mH
C_1	850 µF
C_2	525 µF
Switching frequency (f_s)	40KHz
K_1	5
K_2	10
K_3	0.001
β	0.8
v_{pv}	0-36 volts
r_{pv}	2-14 Ω

To test the V_{ref} tracking mechanism of the proposed DDISMC, the MATLAB/SIMULINK model of the SSI-M6-205 PV panel as shown in Fig.5 has been developed. The proposed DDISMC-MPPT (Fig.3) is applied in this circuit. The tracking response is shown in Fig.6 (a). It needs only one current sensor for measurement of i_C as Jiao's DDISMC-MPPT. Their tracking responses have been compared in Fig.6 (a).

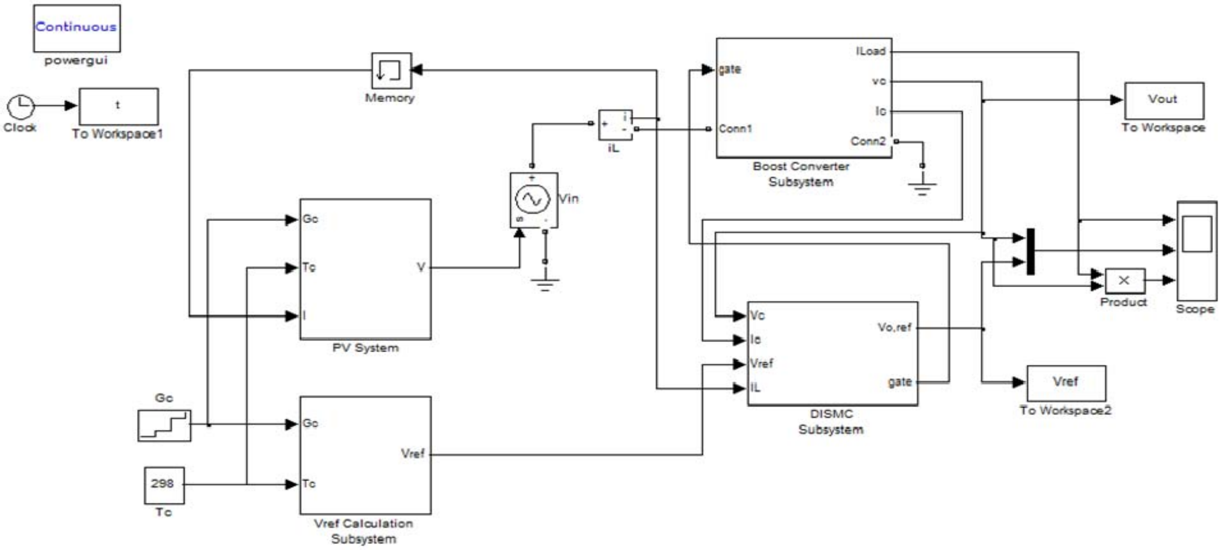
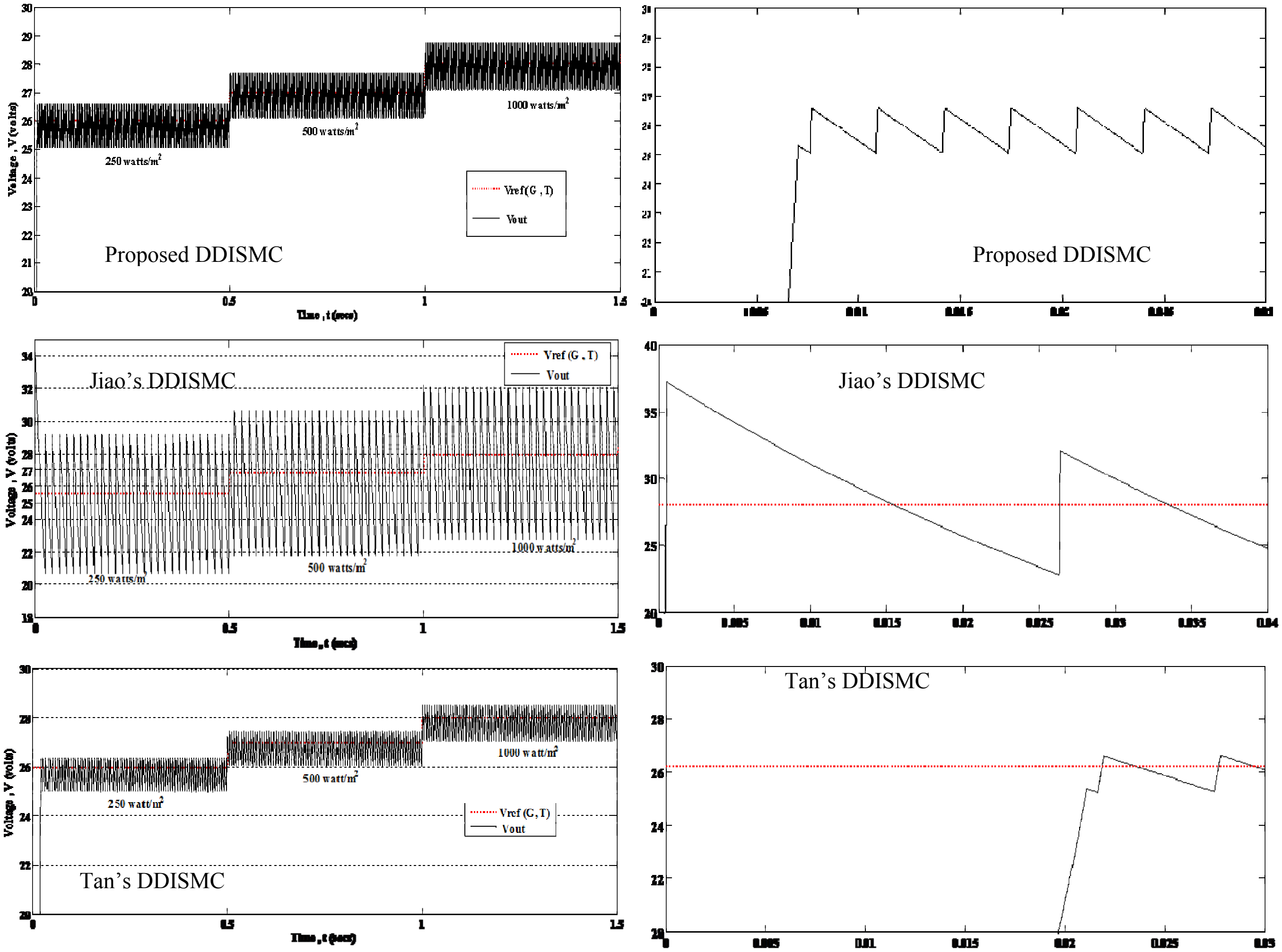


Fig. 5 Block diagram of PV system with Double Integral Sliding Mode Current Controller with two current sensors based MPPT



(a)

(b)

Fig. 6 Comparison of (a) Chattering, (b) Settling time of MPP tracking response for Proposed DDISMC-MPPT, Jiao's DDISMC-MPPT and Tan's DDISMC-MPPT at different solar irradiances

Fig.6 (b) shows a comparison between settling times of the PV panel output voltage signals. From the set figures shown in Fig6 (b), it is clear that, the proposed DDISMC-MPPT with single current sensor has faster response than that of Tan's DDISMC-MPPT. This is because during the start-up, the sliding surface of the DISMC with single current sensor is crossing the origin and the system representing point is very close to origin. Hence, the reaching time is less. Also, the steady state error for the proposed controller is less than that of Jiao's DDISMC-MPPT and almost same with Tan's DDISMC-MPPT. Therefore in this controller the magnitude of steady state error of the output voltage is less. Hence, the proposed DDISMC-MPPT has fast response without affecting its accuracy. Performances of two existing DISMCs together with the proposed DDISMC-MPPT have been provided in Table III.

Table III. Comparison of the proposed DDISMC-MPPT with Tan's DDISMC-MPPT and Jiao's DDISMC-MPPT

Controller Properties	Tan's DDISMC-MPPT	Jiao's DDISMC-MPPT	Proposed DDISMC-MPPT
No. of Current sensors	Two	One	One
Complexity	More	Less	Less
Control Variables	V_{pv}, V_o, i_L & i_C	V_{pv}, V_o, & i_C	V_{pv}, V_o & i_C
Expensive	more	less	less
Reaching time	22 msecs	< 5msecs	8 msecs
Chattering	Less	More	Less

IV. CONCLUSIONS

This paper proposed a DDISMC-MPPT with a new double integral sliding surface for tracking MPPs of a PV system. This DDISMC-MPPT possesses a very simple and efficient PWM-based control structure. The PWM mechanism of this DDISMC-MPPT adds advantages such as simple control structure and fixed frequency operation. Further, the selection of the sliding mode control coefficients taking account the reaching and stability conditions facilitates with fast response and guaranteed stability. The efficacy of the proposed DDISMC-MPPT was verified comparing with two existing DDISMC-MPPTs such as Tan's and Jiao's DDISMC-MPPTs. It is found that with less number of components and control variables compared to Tan's DDISMC-MPPT, the proposed DDISMC-MPPT's reaching time is less than that of Tan's DDISMC-MPPT. Similarly, the proposed DDISMC-MPPT has less chattering compared to the Jiao's DDISMC-MPPT. Hence, the proposed DISMC-MPPT is found to be an efficient MPP tracker for PV system.

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