Design and Simulation of a Modified Sliding Mode Controller Evaluated with a Conventional P&O MPPT Controller for Solar Applications

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Abstract— **This article gives an ample idea about Sliding Mode Controller (SMC) implementation to a DC-DC boost converter for a Solar system to track Maximum Power Point (MPP). SMC implementation accompany three criteria's; they are Hitting, Sliding Mode (SM) Existence and Stability. One diode Photovoltaic (PV) model is designed for lighting applications, and PV output is connected to a boost converter to regulate and enlarge the voltage up to desired level. SMC is implemented in a feedback manner with capacitor voltage and inductor current. The steady state condition occurred less than 0.1sec time, and tracks around 10% more power at Standard Test Conditions (STC). The SMC results are compared with fixed step P & O MPPT controller; the models are simulated in MATLAB/SIMULINK.**

Keywords— DC DC boost converter, MPP, P & O Controller, PV, SMC, STC.

I. Introduction

Photovoltaic's has an outstanding potential as a sustainable energy spawn source due to the ample accessibility of solar power and the resulting contamination free generation of direct current. When the sun rays fall on solar system, it will generate direct current. The PV power generation is based on the principle of the photovoltaic effect [1]. With the arrival of silicon p-n junctions, the photoelectric current is able to produce power due to inherent voltage drop across the junction [2]. However, such power generation is popular for the nonlinear relationship between the current and voltage of the PV cell. There is a unique point at which the solar cell produces maximum power; at this point, the rate of change of power with respect to the voltage is equal to zero [3]. There are various power management issues concerning enhancement in the conversion efficiency of a PV array, thus maximizing PV power output. The two diode model of a PV cell has operated PV array fastly and accurately, but implementation time and cost is more. The maximum power of the PV array changes with shading and/or climatic conditions. The PV output current/voltage changes with solar irradiation levels, whereas the PV output voltage changes with temperature of the PV array [3]. Thus, the primary challenge in a PV system is to ensure that maximum energy is generated from the PV array with a dynamic variation of its output characteristic when connected to a variable load [4]. A solution for this problem is placing a power converter between the PV array and load, which could dynamically change the impedance of the circuit by using a control algorithm [5]. DC DC Converters are required to regulate the output voltage at a required level [6]. In this article, a step up converter is used, that has a potential of providing an output voltage which is higher than the input voltage.

The novel SMC approach is conceded as one of the useful and robust controller for non linear plants operating under changing weather conditions [7] - [14]. Here, in order to approach the SMC, mathematical modeling of SMC should meet the criteria's like hitting, existence and stability, which are part of sliding mode control theory [7]. SMC is to employ a certain sliding surface as a reference path such that the trajectory of the controlled system is directed to the desired equilibrium point [8]. The frequency oscillations may happen in the control process which is reproduced in the actual behavior of the trajectory, called as chattering [12]. The trajectory 'S' chatters along the surface and move towards the origin.

The conventional Perturb and Observe MPPT controller with fixed step size developed by using MATLAB/ SIMULINK. This technique is one of the easiest techniques to track Maximum Power Point [15] - [17]. This MPPT control technique is measuring the changes in PV array current and voltage to predict the effect of voltage change. P and O MPPT controller repeats the process till MPP occurs; afterwards it will change the direction and repeats the process [18]. MPP is located at the knee of the I-V curve [3].

Section II of this article is devoted for a mathematical modeling of a PV cell explanation and results. Section III presents a DC DC boost converter with state space analysis and results. Section IV is committed to design and implementation of modified SMC for a step up converter. Section V shows the implementation of a P and O MPPT controller. Section VI summarizes the comparison and discussion on simulation results (SMC with P & O) and section VII of the paper is ending with conclusions.

II. PV Device Modelling

PV is one of the processes of renewable energy generation mechanisms, which means generating electrical power by converting solar irradiation into direct current [3]. Now, PV is one of the favored renewable energy generation sources due to the ease of access of solar energy and resulting emanation of free generation.

The fundamental circuit of a PV cell is shown in Fig. 1. When the sun rays fall on solar panel, that irradiation converts into direct current. A series resistor, which determines the downward slope of I-V curve in PV cell near V_{oc}, represents the internal resistance of the cell. A shunt resistor, which determines the slope of the line at a top of I-V curve nearer to I_{sc} [2], controls the leakage current from cell to ground, and is

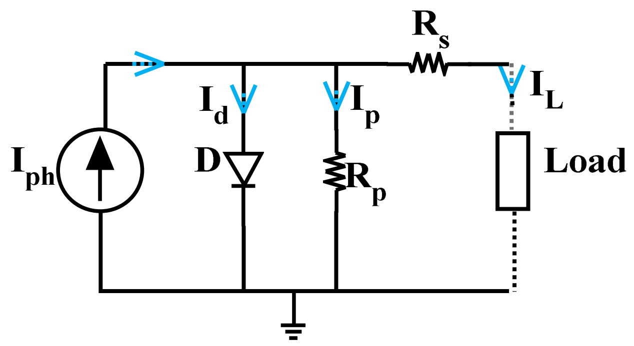

Fig. 1. Circuit of a PV cell single diode model

usually small enough to be neglected. The diode current equation expressed [3] is as follows:

$$I_d = I_0[e^{qv/nkT} - 1] \tag{1}$$

$$I_{pv} - I_d = I_L \tag{2}$$

After solving all the equations, the final expression of PV cell is computed and shown below:

$$V_L = \frac{nkT}{q}\left[\ln\left(\frac{I_{pv} - I_L}{I_0} + 1\right) - \frac{V_L + I_L R_S}{R_p}\right] - I_L R_S \tag{3}$$

After modeling of a PV cell is done, we simulated it in MATLAB/SIMULINK and obtained PV characteristic curves. The waveforms are calculated at STC is shown in Fig. 2. The simulated PV model extracted 23V voltage and 3.4A current. If any temperature or irradiation change occurs in weather, then changes in characteristic curves occurred. Multiple PV characteristic curves at standard temperature and different irradiation levels are shown in Fig. 3. Here the temperature is kept as 25^{o}C and variable irradiation levels as 1000, 800, 600 and 400 respectively.

III. Controller Based Boost Converter

The boost converter is also called as a step up converter; it has a capability of providing surplus output voltage than the input voltage [5], [6]. The circuit diagram of the controller based boost converter is shown in Fig. 4. The boost converter functioning will depends on the switch "ON and OFF". The diode 'D' blocks the reverse flow of current when the switch is turned ON. The current flow is marked with green arrows is shown in Fig. 4.

The mathematical model of a boost converter when the switch is ON can be expressed in state space [3] as follows:

$$\begin{bmatrix} \frac{dI_L}{dt} \\ \frac{dV_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{C_o R_o} \end{bmatrix} \begin{bmatrix} I_L \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{ref} \tag{4}$$

$$V_o = \begin{bmatrix} 0 & -\frac{1}{C_o R_o} \end{bmatrix} \begin{bmatrix} I_L \\ V_o \end{bmatrix} \tag{5}$$

When the switch is OFF, the inductor generates a high voltage to maintain the current i_L in the same direction and now the diode D is forward biased and it starts conducting. The current flow is marked in red arrows is shown in Fig. 4. Hence

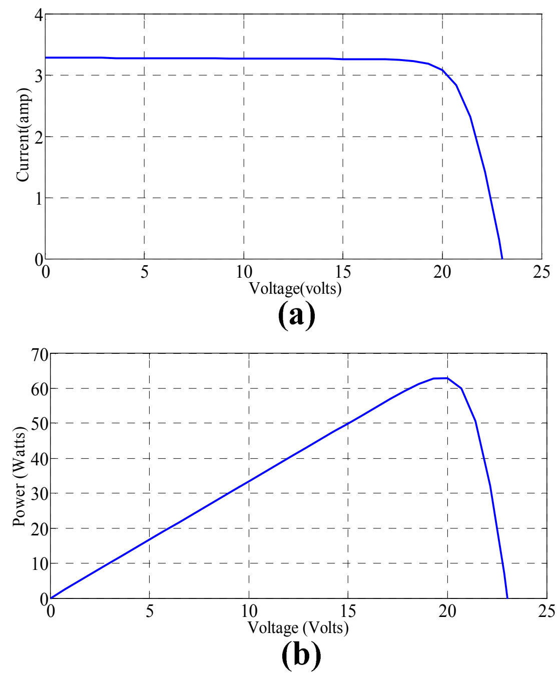

Fig. 2. PV characteristic curves at STC

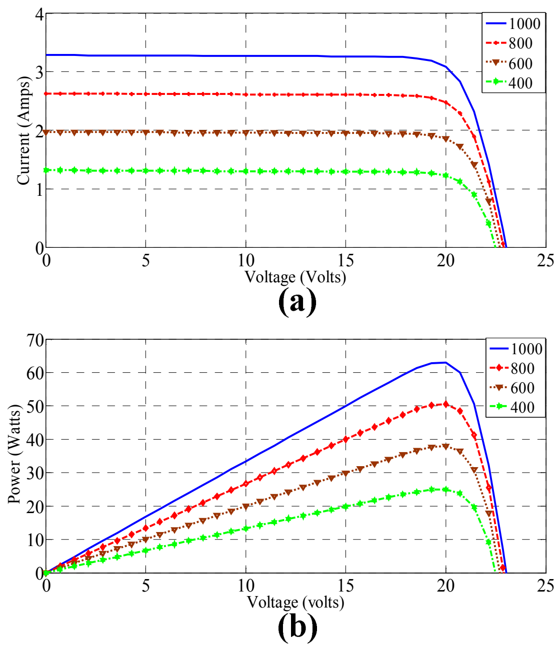

Fig. 3. Characteristic curves of (a) I-V and (b) P-V at different temperatures

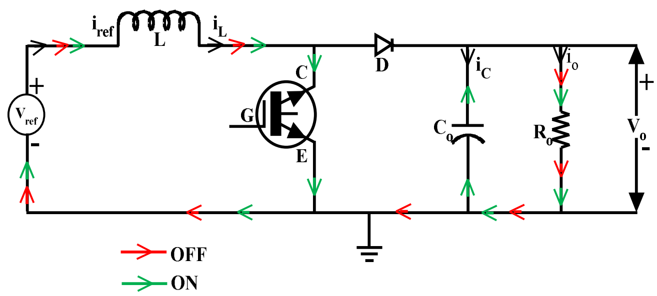

Fig. 4. Conventional Boost Converter Circuit with IGBT

the output voltage can be expressed as

$$V_o = V_{ref} + L\frac{di_L}{dt} \tag{6}$$

The mathematical modeling of a boost converter when the transistor is in OFF state can be expressed in state space as

$$\begin{bmatrix} \frac{dI_L}{dt} \\ \frac{dV_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C_o} & -\frac{1}{C_oR_o} \end{bmatrix} \begin{bmatrix} I_L \\ V_o \end{bmatrix} + \begin{bmatrix} I_L \\ 0 \end{bmatrix} \begin{bmatrix} V_{ref} \end{bmatrix} \tag{7}$$

$$V_o = \begin{bmatrix} \frac{1}{C_o} & -\frac{1}{C_oR_o} \end{bmatrix} \begin{bmatrix} I_L \\ V_o \end{bmatrix} \tag{8}$$

The converter results have taken from different parts of the circuit is shown in Fig. 5. These results are exactly matched with the functioning of the boost converter.

IV. MODIFIED SLIDING MODE CONTROLLER

The MPP with SMC for boost converter is a method which reduces the decay that initiates an additional integral control variable into the constant frequency SMC [7]. The involvement of SMC is to improve the robustness and regulation of the system. Therefore, the aforesaid uses considering the control performance and simplicity of implementation, adopting an SMC is a better option.

The basic principle of an SMC is to design a particular multitudinous its control law [8] that will manage over the trajectory of the state variables around the necessitated operating point. In case of a boost converter as it has a single switch, it is apt to adopt a control law for a switching function as [7]

$$u = \frac{1}{2}\left(1 + sgn(S)\right) \tag{9}$$

In this case, 'S' is illustrated as

$$S = \alpha_i x_i + \alpha_j x_j + \alpha_k x_k = J^T x \tag{10}$$

Where S is a state trajectory, $J^T = \begin{bmatrix} \alpha_i & \alpha_j & \alpha_k \end{bmatrix}$ and $\alpha_i, \alpha_j, \alpha_k$ are the sliding coefficients or control parameters, x=[x_i, x_j, x_k], x_i, x_j, x_k are state feedback variables. By equating S=0, a sliding plane can be obtained. The focus of the designer is to determine the state of switching function 'u' and also to choose appropriate values of α_i, α_j *and* α_k.

A. *Hitting Criteria*

The design of SMC to meet hitting criteria is straight forward in case of power converters. Now the state variables can be expressed in the form of

$$\begin{bmatrix} x_i & x_j & x_k \end{bmatrix}^T = \begin{bmatrix} V_{ref} - \beta V_o & \frac{d(V_{ref} - \beta V_o)}{dt} & \int (V_{ref} - \beta V_o)dt \end{bmatrix}^T \tag{11}$$

In order to design the hitting criteria, x_i state variable is sufficient. The resulting control function in this configuration is

$$u = \begin{cases} 1 = ON, When\ S > 0 \\ 0 = OFF, When\ S < 0 \end{cases} \tag{12}$$

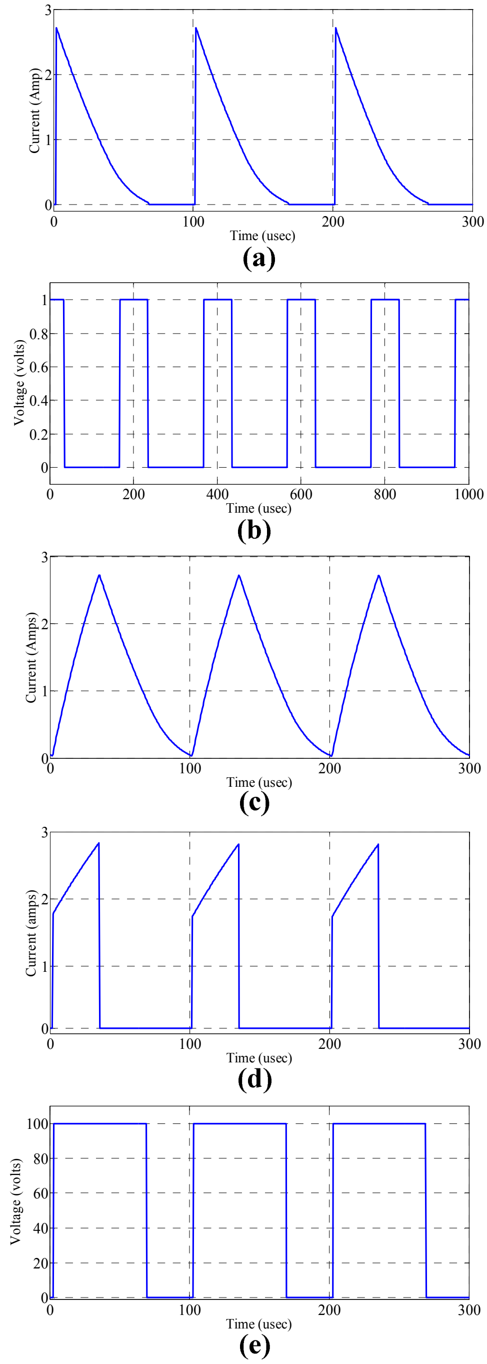

Fig. 5. Results of Boost converter (a) Diode current,(b) Gate voltage,(c) Inductor current, (d) Switch current and (e) Switch voltage.

Thus, the method makes sure the fulfillment of hitting criteria of the SMC.

B. *SM Existence Criteria*

After switching states of the converter determined, the next step is to select α_i, α_j and α_k that fulfills the criteria for SM existence. Now, by assaying a local reachability condition of the state trajectory is

$$\lim_{s \to 0} S.\dot{S} < 0 \tag{13}$$

$$\dot{S} = J^T \dot{x} \tag{14}$$

where $\dot{x} = Ax + Bu$

Case 1: $S \to 0^+, \dot{S} < 0$

Substitution of $\bar{u} = 0$ gives

$$-\alpha_i \frac{\beta i_c}{C} + \alpha_j \frac{\beta i_c}{R_0 C^2} + \alpha_k (V_{ref} - \beta V_o) < 0 \quad (15)$$

Case 2: $S \to 0^-, \dot{S} > 0$

Substitution of $\bar{u} = 1$ gives

$$-\alpha_i \frac{\beta i_c}{C} + \alpha_j \frac{\beta i_c}{R_0 C^2} + \alpha_k (V_{ref} - \beta V_o) - \alpha_j \frac{\beta V_i}{LC} + \alpha_j \frac{\beta V_o}{LC} > 0 \quad (16)$$

Combining the equations (15) and (16), the simplified existence condition is as follows

$$0 < \beta L \left(\frac{\alpha_i}{\alpha_j} - \frac{1}{R_0 C} \right) i_C - LC \frac{\alpha_k}{\alpha_j} (V_{ref} - \beta V_o) < \beta (V_o - V_i) \quad (17)$$

The group of sliding coefficients for the controller must obey to its stated inequalities [14]. This confirms the fulfillment of the SM existence criteria for the converters.

C. Stability Criteria

The selected sliding coefficients (α_i, α_j and α_k) should satisfy the stability condition simultaneously, apart from the fulfillment of SM existence condition. The relation between the sliding coefficients to the dynamic response of the converter during SM operation is

$$\alpha_i x_i + \alpha_j \frac{dx_i}{dt} + \alpha_k \int x_i \, dt = 0 \quad (18)$$

The above equation can be reorganized into standard second order system in which the design of the sliding coefficients will give one of the three possible responses under damped, critical damped and over damped respectively. The selection of sliding coefficients can be easily done by converter response time and voltage peak over shoot specifications.

For an SM voltage controller the switching function 'u' is obtained by the combination of control parameters by utilizing the computation of state trajectories [7].

$$S = \alpha_i x_i + \alpha_j x_j + \alpha_k x_k = J^T x \quad (19)$$

where α_i, α_j and α_k are considered as control parameters.

By imposing S=0, a sliding line is attained. The aim of using sliding line is to serve as a periphery to split the phase trajectory, which reaches and tracks the sliding line declaring the system is stable. The trajectory is at any arbitrary position below the sliding line, u=1 is employed such that the trajectory is going towards the sliding line. Similarly, when the trajectories above the sliding line, u=0 is employed for the trajectory to be directed towards the sliding line. Mathematically expressed as follows:

$$\lambda_1 = (LC \frac{\alpha_k}{\alpha_j} + 1) x_i + LC (\frac{\alpha_i}{\alpha_j} - \frac{1}{LC}) x_j < 0 \quad (20)$$

$$\lambda_2 = (LC \frac{\alpha_k}{\alpha_j} + 1) x_i + LC (\frac{\alpha_i}{\alpha_j} - \frac{1}{R_L C}) x_j - (V_{ref} + \beta V_{in}) > 0 \quad (21)$$

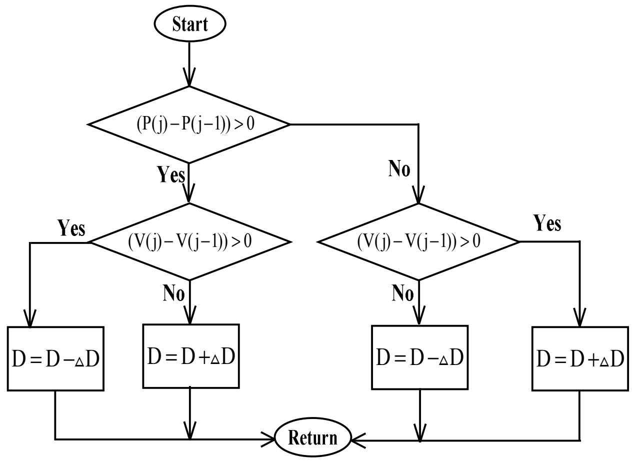

Fig.6. Algorithm of conventional P & O MPPT controller

V. CONVENTIONAL P AND O MPPT CONTROLLER

The Perturb and Observe algorithm operates periodically perturbing the control variable and comparing the PV output power immediately. In an initial P&O MPPT controller using P&O method the adjustment of the operating point is achieved by changing the reference voltage of the controller [18]. The adjustment can be made through the duty cycle "D", and the algorithm is shown in Fig. 6. Note that P(j) and V(j) are the output power and voltage of PV. The power can be calculated from V(j) x I(j) at j^{th} time. D and ΔD are the duty ratio and change in duty ratio.

In-order to attain faster and precise MPPT response under STC, fixed step size perturbation (ΔD) can be required. This will be selected as a function of PV power, denoted as follows:

$$\Delta D(j) = \alpha . \beta \left[P(j) - P(j-1) \right] \quad (22)$$

where α *and* β are the constant value to control the movement towards MPPT and sign step, it depends on perturbation direction.

VI. RESULTS AND DISCUSSION

A P&O MPPT controller is a generic open loop controller; it is one of the commonly used techniques to track MPP. This algorithm is developed with change in duty ratio. Here the outputs of P&O and SMC controllers are presented and verified that, the SMC response time is very quick and tracks excess power than P&O MPPT controller. Simulated results of SMC and P&O controller in MATLAB/SIMULINK are shown in Fig. 7. The electrical parameters of PV array are listed in Table I and tracking performances of the controllers are given in Table II.

VII. CONCLUSIONS

In this article, modified SMC for boost converter is implemented with three basic steps like Hitting, Existence and Stability respectively. The modified SMC tracks PV voltage promptly and reaches steady state condition before 0.1s. The outputs of SMC is compared with a P&O MPPT controller and observed that SMC will reach steady state faster. Mathematical modeling of a PV cell is analyzed and the output of PV array is connected to a DC DC boost converter for voltage regulation. State space analysis of a boost converter is derived and eventually a boost converter based SMC is developed. With the

TABLE I. ELECTRICAL PARAMETERS OF PV ARRAY

Maximum power (P_{max})	62W
Voltage at MPP (V_{MPP})	20V
Current at MPP (I_{MPP})	3.1A
Open circuit voltage (V_{oc})	23V
Short circuit current (I_{SC})	3.36A

TABLE II. COMPARISON OF CONTROLLER OUTPUTS

	SMC	**P&O MPPT**
Output Voltage	250V	237V
Output Current	2.5A	2.36A
Output Power	625W	559.3W

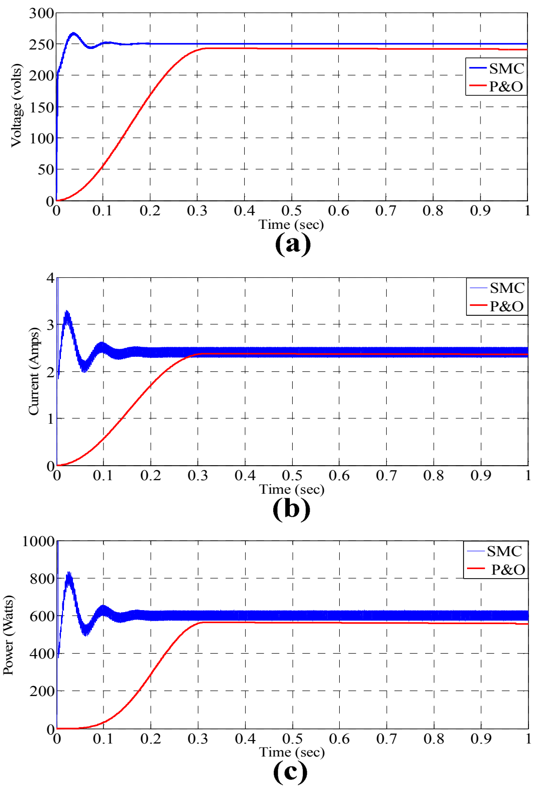

Fig. 7. Outputs of a Boost converter with SMC and conventional P&O MPPT (a) Voltage, (b) Current, (c) Power.

modified SMC, the reference voltage level and steady state conditions occurred quickly and the results were compared with the P&O MPPT controller.

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