Application of Sliding Mode Control in Photovoltaic Application

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Abstract – Photovoltaic system are now-a-days very popular due to abundance and freely availability. However the control techniques for photovoltaic system is a focus of research to improve the power quality. This paper presents PWM based sliding mode control of DC/DC converter in photovoltaic application for power quality improvement. The design methodology is based on two converters viz. Boost and Bi-Directional Buck converters. The performance of control strategy is verified using MATLAB simulations for response to load, line and voltage regulation.

Keywords— Bi-Directional Buck converter, Boost converter, sliding mode controller, continuous conduction mode (CCM), Pulse width modulation (PWM).

I. INTRODUCTION

The continuous decaying of non-renewable energy sources like coal, nuclear, natural gases etc, force us to think towards the renewable energy sources plants like photovoltaic, hydro power plant, wind energy power plant etc. Among all the renewable energy sources photovoltaic is found to be more efficient as compare to others due to the following reasons:

- Easy design and installing of new system.
- Output power meets with the load demand.
- Less maintenance requires.
- Longer lifetime.
- No moving parts.
- Noise free.
- Non-polluting i.e. clean source of energy.

Photovoltaic directly converts solar form of energy into electrical energy. The main conducting device in photovoltaic is the PV cells. Photovoltaic source can produce power for small loads like for mobile charging as well as for the loads of 10 MW and more. Photovoltaic cells produced by the majority of today's most large producer are mainly made of crystalline silicon semiconductor material.

Functioning of photovoltaic cells:

The word of "photovoltaic" consists of two words: photo a Greek word for light, and voltaic, which defines the measurement value by which the activity of the electric field is expressed, i.e. the difference of potentials. PV systems use cells to convert sunlight into electricity. Converting solar energy into electricity in a photovoltaic installation is the most known way of using solar energy.

The principle for photovoltaic power generation is shown in figure below:

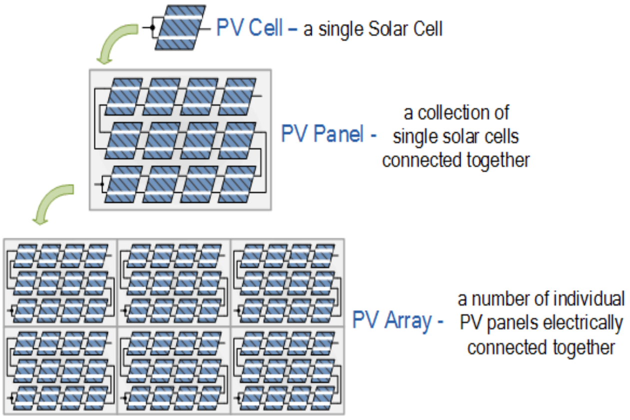

Fig.1 PV cells arrangement

The solar energy is supplied to wireless applications, lighthouses, batteries, various signals, telecommunication equipment and other low power electricity dependent equipment. However battery voltage declines with age. Therefore DC-DC converters are used to regulate voltage. DC-DC converters are electronic devices used whenever we want to change DC electrical power efficiently from one voltage level to another. They're needed because unlike AC, DC can't simply be stepped up or down using a transformer. In many ways, a DC-DC converter is the DC equivalent of a transformer. DC-DC converters have tremendous application in the field of renewable or unconventional energy sources. Since unconventional sources are affected by the natural factors like climate change, temperature, wind speed etc, so we need to maintain output stable voltages. PI & PID controllers are mostly used controller in industries, but they are not suitable for parametric variations, sudden change in load, settling time is more etc.

Theory of Sliding Mode Control provides a systematic approach to controller design while allowing stability in the presence of parametric uncertainties and external disturbances. Sliding mode control (SMC), which is sometimes known as variable structure control (VSC), is characterized by a discontinuous control action which changes structure upon reaching a set of predetermined switching surfaces. This kind of control may result in a very robust system and thus provides a possibility for achieving the goals of high-precision and fast response. Some promising features of SMC are listed below:

- The order of the motion can be reduced
- The motion equation of the sliding mode can be designed linear and homogenous, despite that the original system may be governed by non-linear equations.
- The sliding mode does not depend on the process dynamics, but is determined by parameters selected by the designer.
- Once the sliding motion occurs, the system has invariant properties which make the motion independent of certain system parameter variations and disturbances. Thus the system performance can be completely determined by the dynamics of the sliding manifold.

In this paper, PWM based sliding mode controller is designed and discussed in detail for boost and bi-directional buck converter and results are simulated in MATLAB.

I. SLIDING MODE CONTROL BASICS

For the designing of sliding mode controller we first develop a state space description of the converters (in terms of output voltage, inductor current etc.). The derived expressions are used to define the sliding mode variables. Let say, the expression for sliding function is given by,

$$S = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \dots\dots + \alpha_n x_n \;, \qquad \dots..(1)$$

where

α_1, α_2 & $\alpha_{3,\dots,}$ α_n are sliding co-efficient and x_1, x_2, x_3, ….., x_n are the state space variables.

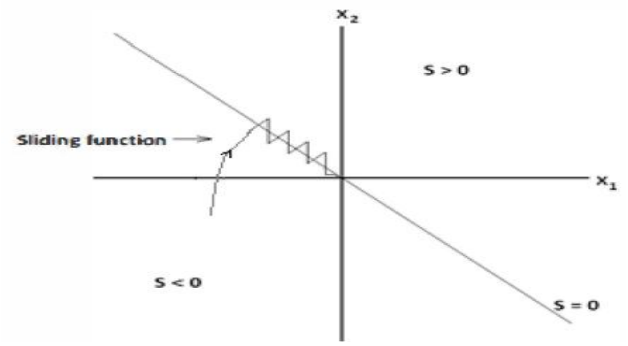

Fig.2 Sliding Surface

In order for the system to work, we have to ensure that the sliding function is confined to the sliding surface, S = O. This is done by applying the existence condition given by:

$$\lim_{s\to 0} S\dot{S} < 0 \qquad \dots\dots.(2)$$

For the figure 2 sliding surface is show by expression S = 0, suppose for two variables, one lies above the sliding surface, sliding function takes positive value and for below the surface it takes the negative value. The derivative of any function gives its slope.

A function ‘S’ is said to positive definite if S(0) = 0and S(x) > 0 for x. It is said to be negative definite if S(0) = 0 and S(x) < 0 for x. This assures that the function is positive definite when it is negative and functions is negative definite if it is positive. In that way the stability is assured.

II. CONVERTER MODELLING

A. *Behavioral modeling of Boost converter:*

Figure 3 shows circuit diagram of boost converter in which R, L and C represents resistor, inductor and capacitor resp. i_L and i_c are the current across inductor and capacitor resp. Vd and Vo are the input and output voltages.

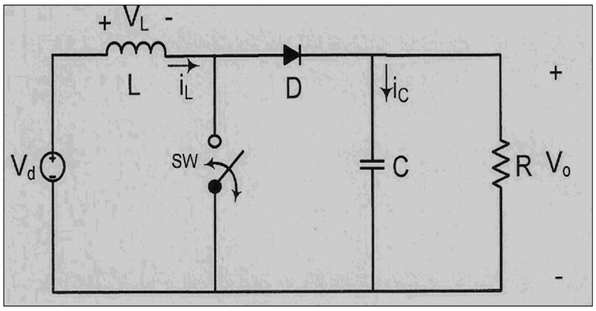

Fig.3 Circuit diagram of Boost converter

Since the condition is continuous conduction mode, so the model will be deduce by applying Kirchhoff’s law. We get,

$$i_L = \frac{1}{L}\int (viu + (vi - vo)\bar{u})dt$$

$$v_o = \frac{1}{C}\int (ic\bar{u} - iR)dt \qquad \dots..(3)$$

where u represents the state of the switch, S and ū is the inverse logic of u.

B. *Behavioral modeling of Bi-Directional buck converter:*

The basic bi-directional dc-dc converter topology is shown in fig. 4 is the combination of a step-up stage together with a step-down stage connected in anti-parallel. For the motor drive operations the converter step-up stage is used to step-up the battery voltage and control the inverter input. The vehicle regenerative braking is accomplished by using the converter step-down stage, which gives a path for the braking current and allows the recovery of the vehicle energy in the battery.

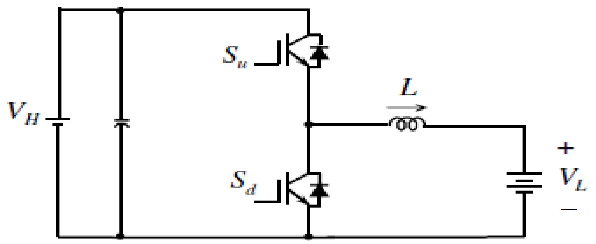

Fig.4 Circuit diagram of Bi-Directional DC/DC buck converter

There are drawbacks relating control like lack of smooth transitions during switching for operation at different modes. For this a complementary switching is used to merge both the controllers.

So a controller is designed for the switch Su, with the complementary output given to Q2. The mathematical expression for the above model can be derived as:

$$iL = \frac{1}{L}\int(vi - vo)dt$$

$$vo = \frac{1}{C}\int(iL - iR)dt \qquad (4)$$

III. CONTROLLER DESIGN METHODOLOGY

In this section, PWM based sliding mode controller is discussed and designed in continuous conduction mode (CCM).

A PID based SM controller is adopted. The control variable used is of the form:

$$x = \begin{bmatrix} x1 \\ x2 \\ x3 \end{bmatrix} = \begin{bmatrix} vref - \beta vo \\ \frac{d}{dt}(vref - \beta vo) \\ \int(vref - \beta vo) \end{bmatrix} \qquad (5)$$

where x1, x2 and x3 are the voltage error, the voltage error dynamics and integral of the voltage error resp. and v_{ref} is the reference voltage.

By substituting the behavioral models of the converters as derived in (3) and (4) in (5), the control variables for boost and bi-directional buck converters are found to be:

$$X_{boost} = \begin{bmatrix} vref - \beta vo \\ \frac{\beta vo}{RLC} + \frac{\beta}{LC}\int(vo - vi)\bar{u}dt \\ \int(vref - \beta vo) \end{bmatrix} \qquad (6)$$

$$X_{bi\text{-}buck} = \begin{bmatrix} vref - \beta vo \\ \frac{\beta vo}{RLC} + \frac{\beta}{LC}\int(vo - viu)dt \\ \int(vref - \beta vo) \end{bmatrix} \qquad (7)$$

Since the control variables makes use of three parameters, from (1), the instantaneous state of the system can be represented by:

$$S = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 \qquad (8)$$

An appropriate sliding mode control law is chosen that makes use of a switching function given by:

$$U = \begin{cases} 1 & when\, S > 0 \\ 0 & when\, S < 0 \end{cases} \qquad (9)$$

B. Derivation of existence conditions

For SM controller to work, (2) should be satisfied. i.e:

$$\lim_{S \to 0} S\dot{S} < 0$$

Boost Converter Existence Condition:

For the boost converter:

$$\dot{S} = \alpha_1 \frac{d}{dt}(vref - \beta\frac{1}{c}\int ic\ dt) + \alpha 2\frac{d}{dt}(\frac{\beta vo}{RLC}) + \frac{\beta}{LC}\int(vo - vi\bar{u}\ dt) + \alpha 3ddtvref - \beta vodt \qquad (10)$$

Two cases arise as shown:

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

Substituting (9) in (10):

$$-\alpha_1\frac{\beta ic}{c} + \alpha_2\left(\frac{\beta ic}{RLC\,2}\right) + \alpha_3(vref - \beta v0) < 0 \qquad (11)$$

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

Substituting (9) in (10):

$$-\alpha_1\frac{\beta ic}{c} + \alpha_2\left(\frac{\beta ic}{RLC\,2} + \frac{\beta vo}{LC} + \frac{\beta vi}{LC}\right) + \alpha_3(vref - \beta v_0) > 0 \qquad (12)$$

From (11) and (12), the existence condition for boost converter is found to be:

$$0 < \beta L\left(\frac{\alpha 1}{\alpha 2} - \frac{1}{RLC}\right) ic - LC\frac{\alpha 3}{\alpha 2}(vref - \beta vo) < \beta(vo - vi) \qquad (13)$$

The existence condition is used to arrive at the expression for ramp voltage and control voltage. This is done by applying the duty cycle constraint to (13), yielding the expression:

$$0 < \frac{\beta(vo - vi) - \beta L\left(\frac{\alpha 1}{\alpha 2} - \frac{1}{RLC}\right)ic + LC\frac{\alpha 3}{\alpha 2}(vref - \beta v0)}{\beta\ (vo - vi)} < 1 \qquad (14)$$

Using (14), the expression for control and ramp voltages are chosen as:

$$V_{control} = -K_{p1}i_c + K_{p2}(v_{ref} - \beta v_o) + \beta(v_o - v_i) \qquad (15)$$

$$V_{ramp} = \beta(v_o - v_i) \qquad (16)$$

Where $K_{p1} = \beta L\left(\frac{\alpha 1}{\alpha 2} - \frac{1}{RLC}\right)$, $K_{p2} = LC\left(\frac{\alpha 3}{\alpha 2}\right)$ and β = feedback factor.

1) *Bi-directional Buck Converter Existence Condition:*

For the bi-directional buck converter:

$$\dot{S} = \alpha_1\frac{d}{dt}(vref - \beta\frac{1}{c}\int ic\,dt) + \alpha 2\frac{d}{dt}(\frac{\beta vo}{RLC} + \frac{\beta}{LC}\int(vo - viu\,dt) + \alpha 3ddtvref - \beta vodt \quad (17)$$

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

Substituting (9) in (17), the following expression is obtained:

$$-\alpha_1\frac{\beta ic}{c} + \alpha_2\left(\frac{\beta ic}{RLC\,2} + \frac{\beta vo}{LC} - \frac{\beta vi}{LC}\right) + \alpha_3(v_{ref} - \beta v_o) < 0 \quad (18)$$

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

Substituting (9) in (17):

$$-\alpha_1\frac{\beta ic}{c} + \alpha_2\left(\frac{\beta ic}{RLC2} + \frac{\beta vo}{LC}\right) + \alpha_3(v_{ref} - \beta v_o) > 0 \quad (19)$$

From (18) and (19), the existence condition is found to be:

$$0 < -\beta L\left(\frac{\alpha 1}{\alpha 2} - \frac{1}{RLC}\right) ic - LC\frac{\alpha 3}{\alpha 2}(v_{ref} - \beta v_o) + \beta v_o < \beta v_i \quad (20)$$

Applying the duty cycle constraints to (20) yields the expression:

$$0 < \frac{-\beta L\left(\frac{\alpha 1}{\alpha 2} - \frac{1}{RLC}\right)ic + LC\frac{\alpha 3}{\alpha 2}(vref - \beta v0) + \beta vo}{\beta vi} < 1 \quad (21)$$

where $K_{p1} = \beta L\left(\frac{\alpha 1}{\alpha 2} - \frac{1}{RLC}\right)$, $K_{p2} = LC\left(\frac{\alpha 3}{\alpha 2}\right)$ and β = feedback factor.

Hence the expression for control and ramp voltages are:

$$V_{control} = -K_{p1}i_c + K_{p2}(v_{ref} - \beta v_o) + \beta v_o \quad (22)$$

$$V_{ramp} = \beta v_i \quad (23)$$

The constants α_1, α_2, α_3 are selected with the help of the following equations:

$$\frac{\alpha 1}{\alpha 2} = \frac{10}{Ts} \quad (24)$$

$$\frac{\alpha 1}{\alpha 2} = \frac{25}{\partial 2Ts2} \quad (25)$$

Where Ts is the desired settling time and ∂ is the damping constant. The damping constant can be selected by making use of the desired peak overshoot percentage Mp as below:

$$\partial = \sqrt{\frac{\left(\ln\frac{Mp}{100}\right)2}{\pi 2 + \left(\ln\frac{Mp}{100}\right)2}} \quad (26)$$

The above equations are used to calculate Kp1 and Kp2 for both the converters. The specifications for boost and bi-directional buck converters are shown in table I & table II resp.

IV. SYSTEM MODELLING

Fig 5 and Fig 6 shows the resulting controller schematics for boost and bi-directional buck converters as per the derivative above.

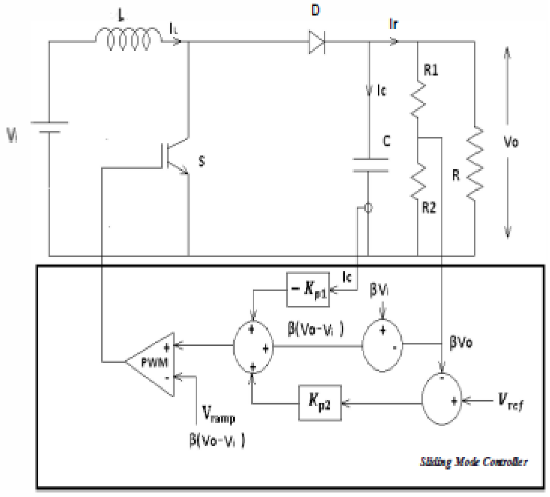

Fig.5 PWM based sliding mode controller for boost converter.

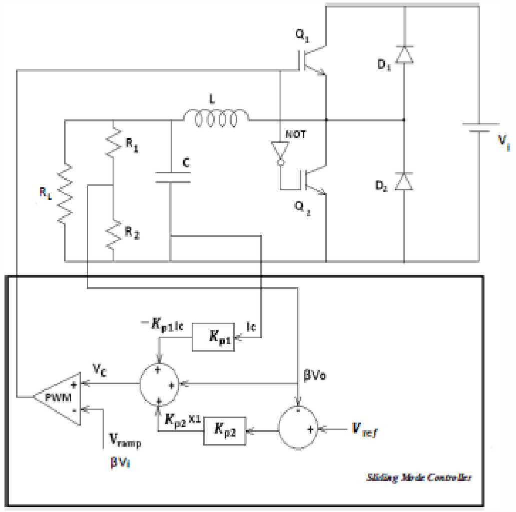

Fig.6 PWM based sliding mode controller for bi-directional converter.

V. SIMULATION, RESULT & DISCUSSION

The simulink models of photovoltaic system, sliding mode control for boost converter and bi-directional buck converter is shown below in fig. 7, fig. 8, fig. 9.

6.1 Model for Photovoltaic system:

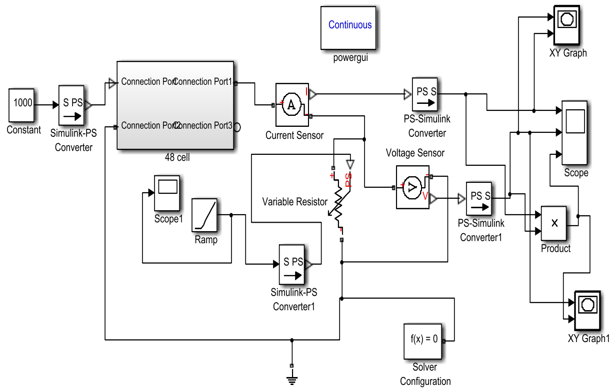

Fig.7 Simulation model for photovoltaic system.

6.2 Model and result for Boost Converter:

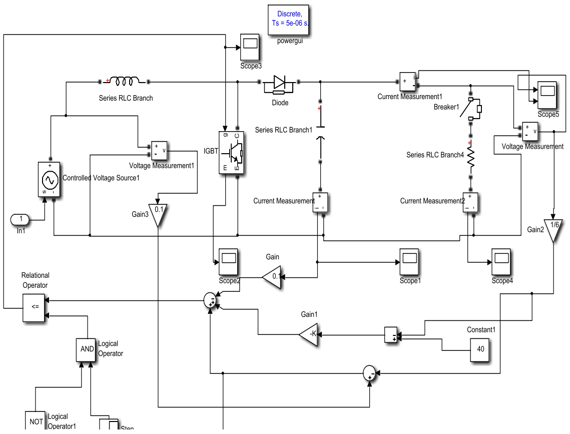

Fig.8 Simulation model for Boost converter

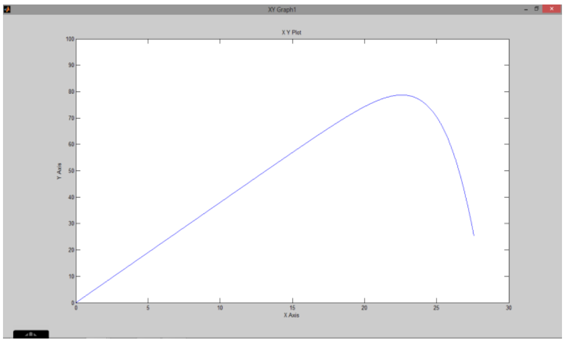

Fig.9 P-V characteristic of photovoltaic system

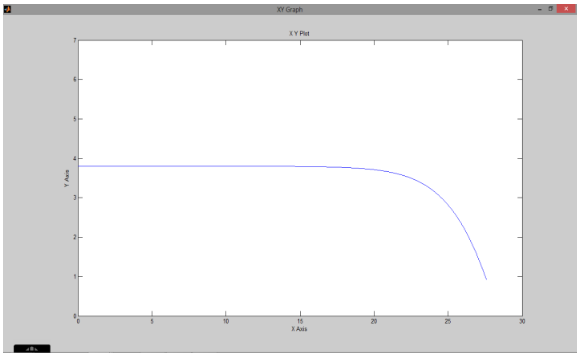

Fig.10 I-V characteristic of photovoltaic system

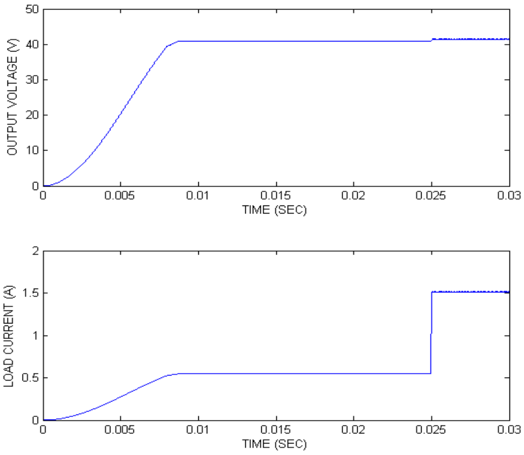

Fig.9 Output voltage and load current of boost converter for step change in load

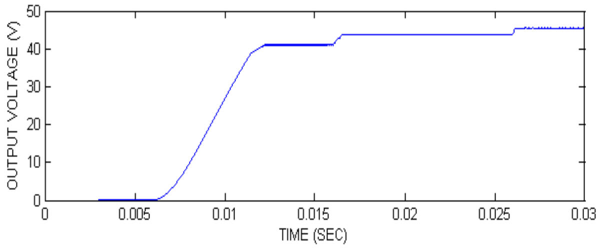

Fig.10 Output voltage of boost converter during voltage regulation

6.3 Model and result for Bi-Directional Buck Converter:

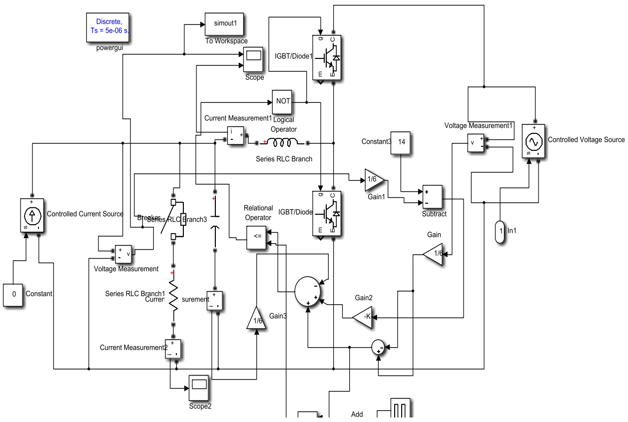

Fig11 Simulation model for Bi-Directional buck converter

In this paper, PWM based sliding mode controller for DC/DC boost and bi-directional buck converter has been design and simulated. This paper shows the simulated results for output voltage (V) and load current (A). the controller response to line, load and voltage regulation is tested and the inferences are drawn.

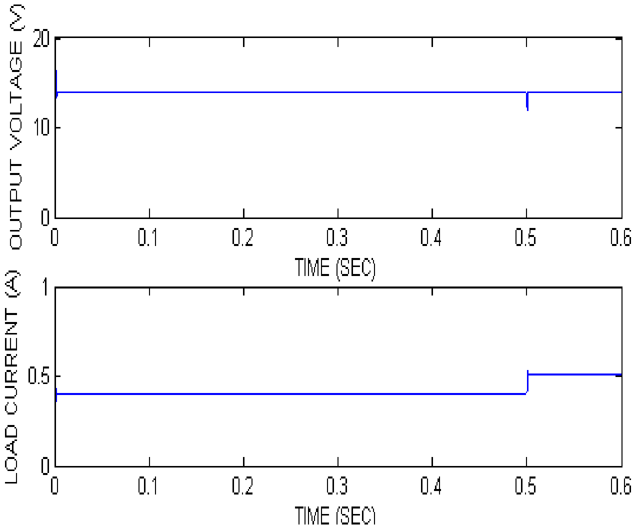

Fig.12 Output voltage and load current of bi-directional buck converter for step change9 in load

The results of simulation are shown in fig. 9, 10, 12 and 13. In fig.9 for boost converter, the output voltage changes from 27.5V to 42V in the 0.03 sec with linearity. The result of output current shows the ability of the controller to maintain constant output voltage across load when the load is changed at t = 0.025 sec from 55Ω to 25Ω. Fig.10 shows the output response of the boost converter to the controller input when the desired voltage is changed at t = 0.012 sec from 41V to 44V and at t = 0.026 sec when desired voltage is changed from 44V to 46V.

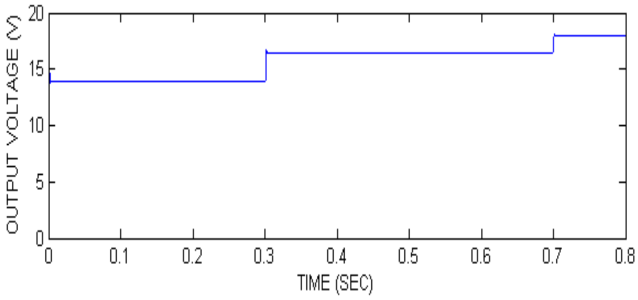

Fig.13 Output voltage of bi-directional buck converter during voltage regulation

In fig.11, for bi-directional buck converter, the output voltages changes from 27.5V to 14V in t = 0.6 sec with linearity. At t = 0.5 sec, there is sudden change in load, but voltage across this will be constant, this shows the ability of the controller in sudden change of load. Fig. 12 shows the output response of the bi-directional buck converter to the controller input when the desired voltage is changed at t = 0.3 sec from 14V to 16.5V and at t = 0.7 sec when desired voltage changes from 16.5V to 18V. Thus from the above results we can see that the designed controllers show good response and are able to maintain constant output voltage in all conditions.

VI. CONCLUSION

PWM based sliding mode controller is designed for boost and bi-directional buck converter using photovoltaic system. Simulink model of the PV system connected to a DC/DC boost converter was used to verify the outcome of the proposed MPP tracking controller. Results are satisfactory and it illustrate a fast converging speed to the MPP of the PV system They show the superior response to line, load and voltage variations.

VII. APPENDIX

Boost Converter parameter:

Load Resistance R = 25Ω,

Inductance L = 30mH,

Capacitance C = 450µF,

Switching frequency f = 10000Hz,

Input Voltage v_i = 27.5V,

Feedback factor β = 1/6

Buck Converter parameter:

Load Resistance R = 25Ω,

Inductance L = 10mH,

Capacitance C = 10µF,

Switching frequency f = 10000Hz,

Input Voltage v_i = 27.5V,

Feedback factor β = 1/6

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