# Comparative Analysis of Sliding Mode Control and PI Controller for Boost Convereter for Distributed Energy Systems

Udaya Bhasker Manthati,
Department of Electrical Engineering
NIT-Warangal,Telengana,India
e-mail: ub@nitw.ac.in

K M Annu,
Department of Electrical Engineering
NIT-Warangal,Telengana,India
e-mail: annugudiya2@gmail.com

Srinivas Punna
Department of Electrical Engineering
NIT-Warangal,Telengana,India
e-mail: srinu240@gmail.com

***Abstract*—A comparative analysis of sliding mode control and PI controller for the operation of boost converter is presented in this paper. Proportional (P), Proportional Integral (PI), Proportional Integral Derivative (PID) controllers are the widespread linear control technique which are very ordinary and less costly for adjustment to a particular specification or requirement. Many industries use these controllers. On the other hand there is one non-linear sliding mode control (SMC) technique. It has many advantages like fast dynamical response, ingrained robust features of SMC. In the present paper, the boost converter is modeled and Pulse Width Modulation (PWM) based SMC and PI controllers are designed and simulated using MATLAB/SIMULINK. SMC and PI controller performance areanalyzed and compared and the results are projected.**

***Keywords-Distributed Generation (DG);Photo Voltaic; Boost Converter; Sliding Mode Controller (SMC); PI Controller;Pulse Width Modulation (PWM)***

## I. INTRODUCTION

In particular solar energy is an effective alternate energy source to provide electrical energy. Photo Voltaic(PV) systems have high installation cost, this is a drawback of PV so for decreasing installation cost, efficiency of the PV system has to be increased. For this power electronic (PE) interface is very much essential and vital. Boost converter is a PE interface to increase voltage level, gain and efficiency. This can be applied to a stand-alone system or of grid connected system such as DC/AC μ-grid.

The transient response and steady sate response of any converter depends upon its pole–zero location. Here in this paper control and stability operation of boost converter is being studied. In control to output voltage transfer function there is one right half plane zero (RHPZ) which makes the response of system slothful especially when control depends upon only output voltage [1]. So a different approach is used for this which is current mode control (CMC) but only CMC does not uphold applications of converter over a wide range of operating conditions [2]. In this paper a fixed frequency PWM based sliding mode controller is used which has both voltage and current mode control to regulate output voltage and input current which is inductor current [3].CMC of boost converter transforms an input voltage $v_i(t)$into an output voltage, $v_o(t)$sothat the peak inductor current $i_{L,peak}$ be controlled and always remain inferior to a reference current.

A non-linear SMC has many advantages like: 1. Order reduction of the system, 2. Better large signal control performance, 3. Fast dynamic response, 4. Stabile for low voltage overshoots, less variation of settling time, robust structure of SM control etc.., SM current controller is reflected on a reigning method to make a robust closed loop system against uncertainness of intrinsic (input) and extrinsic (output) perturbations. Discontinuities operation of the SM controller causes chattering phenomenon. The use of SMC in real application is limited by chattering. Much of the works and research on elimination of chattering of SMC is being done and this is the main objective of researchers of SMC.Industries and educational institutes have been using a linear PI control technique for many decades. This technique is used for the closed loop operation of power electronics converters due to its simplicity, less cost, easy implement, controller constant ($k_p$, $k_i$, $k_d$) calculations, etc..,. It also gives less settling time, rise time and less harmonics [4].

In this paper both controllers are compared for load disturbance and input disturbance for a Photovoltaic system. PV power generation is of intermittent in nature. It should be interfaced with boost converter. And inter connected to a storage system. Independent control is proposed to each distributed energy source. This paper analyzes the behavior of both controllers and verified which controller performance is better in the case of disturbance. The organization of paper is as follows. In Section II modeling of boost converter is discussed. In Section III designing of SM controller is shown. In Section IV design of PI controller is discussed. In Section V simulation results of both controllers are analyzed. For this time domain analysis is done using MATLAB/SIMULINK which shows settling time, rise time, overshoots and ripples during disturbance and after disturbance etc…, Conclusion and future scope of SM current controller are discussed in the last section.

## II. MODELING OF DC-DC BOOST CONVERTER

Modeling of non–isolated boost converter is done by using state-space averaging technique by writing equations for the switch ON and OFF condition [2].

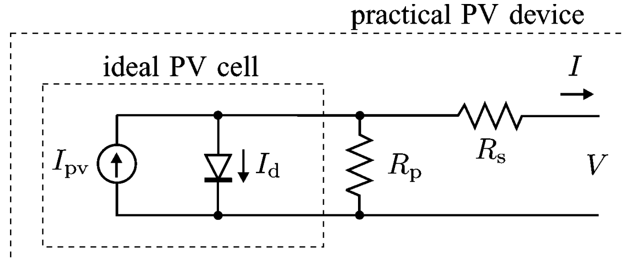


**Figure1: equivalent circuit of a PV cell**

978-1-7281-3848-0/19/$31.00 ©2019 IEEE
DOI 10.1109/ICSGSC.2019.00013

For modelling and simulation of boost converter and controllers battery is used in place of PV panel in this paper. The equivalent circuit of PV cell is shown as follows:

The governing equations of PV cell are:

$$I_{sc} - I_D - \frac{V_D}{R_p} - I_{PV} = 0$$

*Diode* characteristic $I_D = I_0(e^{\frac{V_D}{V_T}} - 1)$

$V_{PVcell} = V_D - R_s I_{PV}$

Where $I_{SC}$: short circuit current of a PV cell, $I_D$: Diode Current, $V_D$: Voltage drop across diode, $I_0$: initial current, $R_s$: Series Resistance, $R_p$: Parallel Resistance

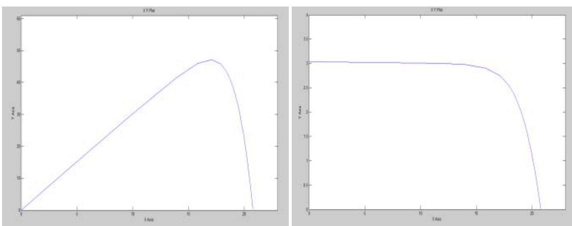

**Figure2: P-V Characteristic curve and I-V Characteristic curve**

Circuit diagram of a Boost converter with PV panel is shown in Fig3. When switch is ON, diode is reverse biased.

$$i_L = \frac{1}{L}\int V_i \, u dt \quad (1)$$

$$\frac{dv_0}{dt} = -\frac{v_0}{RC} \quad (2)$$

When switch is OFF, diode is forward biased

$$i_L = \frac{1}{L}\int (v_i - v_0)\, \bar{u} dt \quad (3)$$

$$V_0 = \frac{1}{C}\int i_c \, dt \quad (4)$$

Combine equations (1) and (3)

$$i_L = \frac{1}{C}\int (V_i u + (V_i - V_0)\bar{u}) dt \quad (5)$$

Where states of the switch is indicated by $u$ and $\bar{u}$ = 1- $u$.

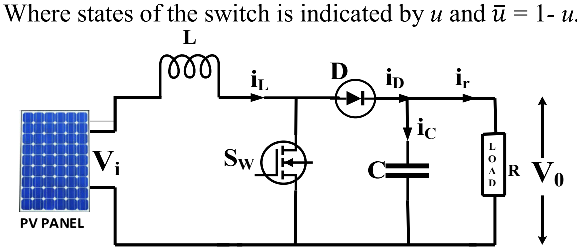


**Figure3.** Boost converter

Where (0, 1) are the two switch position of u and $\bar{u}$. Switch position has the vital role of the control input. In average model duty cycle is denoted by control input u of one switching period. Sliding mode works on very high switching frequency. For high switching frequencies the average model is valid.

## III. Design Procedure for SM Controller

Controllers are needed to control the parameters of every plant according to desired output. A general block diagram of controller controlling the boost converter is shown in Figure 4.

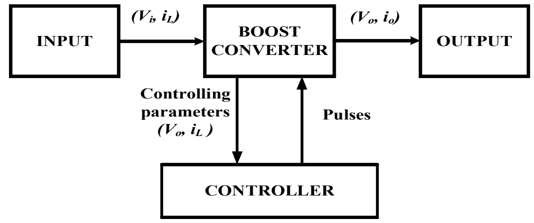


**Figure 4.** General block diagram of control system

### A. Design of SM controller

In design procedure of fixed frequency SM controller which has both controlled parameter output. i.e. inductor current and output voltage. A reference current for inductor is generated using voltage profile

$$i_{ref} = K(V_{ref} - \beta V_o) \quad (6)$$

So that at steady state $V_{ref} = \beta V_{o(ss)}$ and $I_{ref(ss)} = I_{L(ss)}$ where $V_{ref}$ is reference voltage and β feedback network ratio and '$K$' is amplified gain of the voltage error. '$K$' should be large to improve dynamic response and to minimize the steady state voltage error of the system.

For sliding mode controller there is a sliding surface of the controller, using error function as state variable, so that when sliding surface $S = 0$, error is zero. To drive surface along zero there is a switching function which is known as $u = \frac{1}{2}(1 + sign(S))$. This controller uses a sliding surface $S = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3$ where $\alpha_1$, $\alpha_2$, $\alpha_3$ are sliding coefficients and state variable are $x_1$, $x_2$, $x_3$ which are expressed as

$$\left.\begin{aligned} x_1 &= i_{ref} - i_L \\ x_2 &= V_{ref} - \beta V_o \\ x_3 &= \int (i_{ref} - i_L) dt + \int (V_{ref} - \beta V_o) dt \end{aligned}\right\} \quad (7)$$

where instantaneous inductor current is expressed as $i_L$. In the case of fixed frequency SM controller, to remove steady state error, integral terms of voltage and current error are introduced as $x_3$. To procure equivalent control signal for this controller, $\frac{dS}{dt} = \alpha_1 \dot{x}_1 + \alpha_2 \dot{x}_2 + \alpha_3 \dot{x}_3 = 0$ is done [4], it gives

$$u_{eq} = 1 - \frac{K_2}{v_o} i_C - \frac{K_3}{v_o} i_L + \frac{K_1}{v_o}[V_{ref} - \beta v_o] - \frac{v_i}{v_o} \quad (8)$$

Where fixed gain parameters of the proposed controller

$$K_1 = \frac{\alpha_3}{\alpha_1} L[K + 1]; \; K_2 = \frac{\beta L}{C}\left[K + \frac{\alpha_2}{\alpha_1}\right]; \; K_3 = \frac{\alpha_3}{\alpha_1} L \quad (9)$$

### B. Structure of SM controller

The PWM technique is used to operate SM current controller by using a set of control laws. It gives static and dynamic behavior of SM controller. The control laws comprise a ramp signal or reference signal $v_{ramp}$ and a control signal $v_c$ , after solving dynamical behavior of the controller , inherits the expression

$$\left.\begin{aligned} v_c &= G_s[v_o - v_i] + G_s K_1[V_{ref} - \beta v_o] \\ &\quad - G_s K_2 i_c - G_s K_3 i_L \\ v_{ramp} &= G_s v_0 \end{aligned}\right\} \quad (10)$$

In equation (10) $G_s$ is a down scaling factor and an assumption $\beta = G_s$ is made. There is no need to take variable voltage peak for ramp signal and no need of logic AND operator with pulses of pulse generator to make duty cycle < 1. It can be controlled or saturated by control signal according to ramp signal, so that $0 < v_c < v_{ramp}$ always.

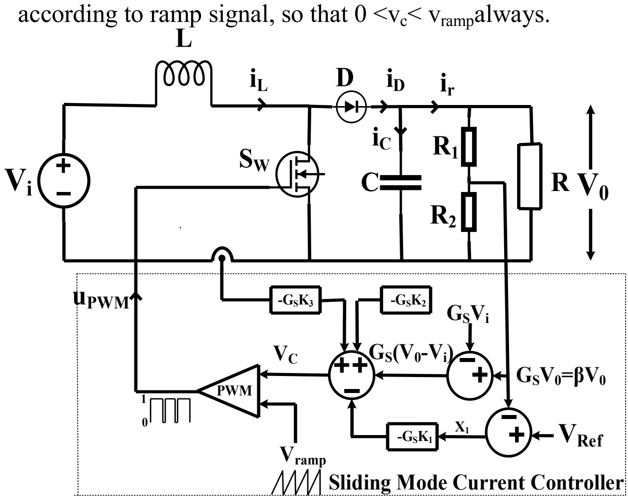


**Figure 5.** SM controller for Boost Converter

An overview of the proposed SM controller is shown in Figure 5. In this controller an inductor current sensor is an additional and the main component to get faster response of RHPZ converter system.

## C. Necessary conditions for the SM operation

Hitting, existing and stability conditions are the three main conditions for occurrence of SM operation.

### 1. Hitting Condition

The sliding surface trajectory should move within a vicinity δ of the sliding manifold, irrespective of the initial conditions of locations. This is the main purpose of hitting condition. It has been satisfied by the appropriate choice of the switching function. The physical representation of the hitting condition is illustrated in Figure 6.

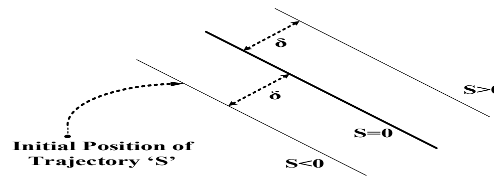


**Figure 6.** Hitting condition

### 2. Existing Condition

By making the condition of local reach ability, the existence of sliding mode operation can be satisfied i.e. $\lim_{S\to 0} S\frac{dS}{dt} < 0$, by substitutions of sliding surface equation and its time derivative, gives

$$\alpha_1\left[-\frac{v_i}{L} - \frac{\beta K}{C} i_c\right] - \alpha_2 \frac{\beta}{C} i_c + \alpha_3\left((K+1)[V_{ref} - \beta v_o] - i_L\right) < 0$$

$$\alpha_1\left[-\frac{v_i - v_o}{L} - \frac{\beta K}{C} i_c\right] - \alpha_2 \frac{\beta}{C} i_c + \alpha_3\left((K+1)[V_{ref} - \beta v_o] - i_L\right) > 0 \quad (11)$$

For steady state operations static sliding surface of controller is designed to meet existence condition [5-12] and taking into account of (9) and (11) can be simplified as

$$\left.\begin{aligned} 0 &< v_{imin} - K_1[V_{ref} - \beta v_{o(ss)}] + K_2 i_{C(min)} + K_3 i_{L(max)} \\ v_{imax} &- K_1[V_{ref} - \beta v_{0(ss)}] + K_2 i_{cmax} + K_3 i_{Lmin} < v_{o(ss)} \end{aligned}\right\} \quad (12)$$

### 3) Stability Condition

Sliding manifold directs trajectory near to a stable equilibrium point. If trajectory is near to equilibrium point, SM system will be stable otherwise it won't be.

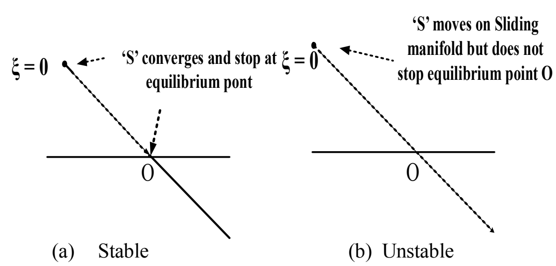


**Figure 7**. Stability condition for sliding manifold (a) Stable (b) Unstable

Stability and instability conditions are illustrated in Figure 7. For SM controller there are three steps for analyzing stability condition, one is ideal sliding dynamics in which $\bar{u}$ is replaced by $\overline{u_{eq}}$. By this discontinuous system can be converted into an ideal sliding mode continuous system [13].The second step is equilibrium point analysis. At the equilibrium point, without input or loading disturbance there is no change in system's dynamics. The third step is linearization of ideal sliding dynamics around the equilibrium point [13].

After solving many equations for these three conditions [13], the two equations must be satisfied.

$$\left.\begin{array}{l} K_3\frac{V_iRC}{L\beta V_O}+\frac{V_i}{\beta V_o}<K_1,\text{ when } K_2>\frac{V_{iR}}{V_o} \\ K_3\frac{V_iRC}{L\beta V_O}+\frac{V_i}{\beta V_o}<K_1,\text{ when } K_2<\frac{V_{iR}}{V_o} \end{array}\right\} \quad (13)$$

And the second equation for stability is

$$2K_3V_o^3(K_2-K_1\beta R) + V_iV_o^2K_2(K_1\beta R-2K_2) + V_i^2V_oR(3K_2-K_1\beta R) - V_i^3R^2>0 \quad (14)$$

For designing of SM current controller the selection of control gains and fixed gain parameters are done with the help of equations (12), (13) and (14).

## IV. DESIGN PROCEDURE OF PI CONTROLLER

The proportional control mode changes the control signal in proportion to the error signal *(e)* and the adjustable setting called the proportional gain *($K_p$)*.The integral control mode produces a corrective change in the controller outputby driving the error offset to zero and the adjustable setting is termed integral time constant *($T_i$)* [14]. A general PI controller block diagram is shown in Fig. 8.

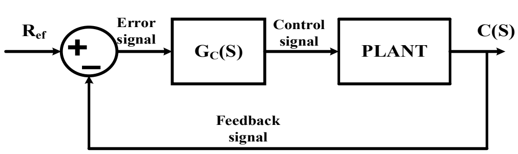


**Figure 8**. Block diagram of a simple PI controller

In this paper Ziegler and Nichols method is used for determining values of the proportional gain *($K_p$)*integral time *($T_i$)* based on the transient response characteristics of a given plant. In this method we first set $T_i = \infty$. The value of*($K_p$)* that makes the system marginally stable so that sustained oscillation occurs can be obtained by use of Routh's Hurwitz stability criterion. For that, calculated control to output transfer function and characteristics equation for the closed loop system with *($K_i$)* is written.By examining the coefficients of the first column of the Routh table it is find that sustained oscillation will occur if $K_{cr}$= 0.01041 then it is put into characteristic equation and frequency of sustained oscillation is found by putting $s = j\omega$. And it is got ω= $0.268\cdot10^4$rad/s then period of sustained oscillation is calculated.

$P_{cr} = 2\pi/\omega = 2.34\cdot10^{-3}$

**TABLE 1** – ZIEGLER – NICHOLS TUNING RULE BASED ON CRITICAL GAIN$K_{cr}$ AND CRITICAL PERIOD $P_{cr}$

| Type of Controller | $K_P$ | $T_i$ | $T_d$ |
|---|---|---|---|
| P | $0.5K_{cr}$ | ∞ | 0 |
| PI | $0.45K_{cr}$ | $P_{cr}/1.2$ | 0 |
| PID | $0.6K_{cr}$ | $0.5\ P_{cr}$ | $0.125\ P_{cr}$ |

So from this table,

$K_P$= 0.45·0.01041

$K_p = 4.68\cdot10^{-3}$, $T_i$= $1.95\cdot10^{-3}$

Total PI controller gain: $G_C = K_p(1+1/T_is)$, $K_i$= 2.4

## V. RESULTS AND ANALYSIS

The designed indirect SM current controller and PI controller tuned using Ziegler–Nichols method for boost converter are implemented in MATLAB/SIMULINK. Specifications for simulation of boost converter are given in the table.

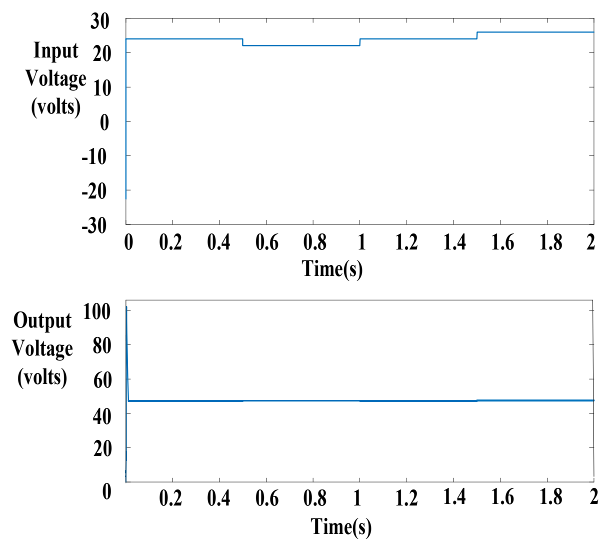


**Figure9**.Voltage waveforms for SM current control technique

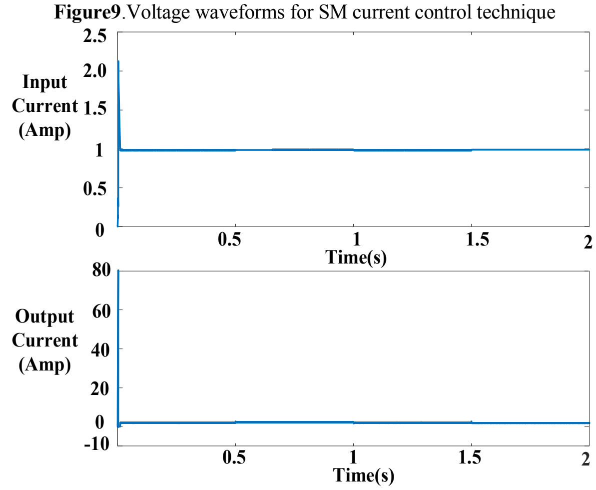


**Figure 10**.Current waveforms for SM current control technique

For the given limitations in equations (12), (13) and (14) the values of the control gain and fixed gain parameters for SM operation are $V_{ref}$ = 6V, $G_s$= β = 1/8, $K_1$ = 79, $K_2$ = 3.10, $K_3$ = 2.65. Control parameters for PI controller are given in design of PI controller (IV). A comparison analysis is done for the results of SM controller and PI controller. It is shown here in the terms of settling time, rise time, peak overshoot, peak to peak ripple in output voltage and peak to peak ripples in inductor current. The behavior of both controllers is seen when disturbance is given in input side.

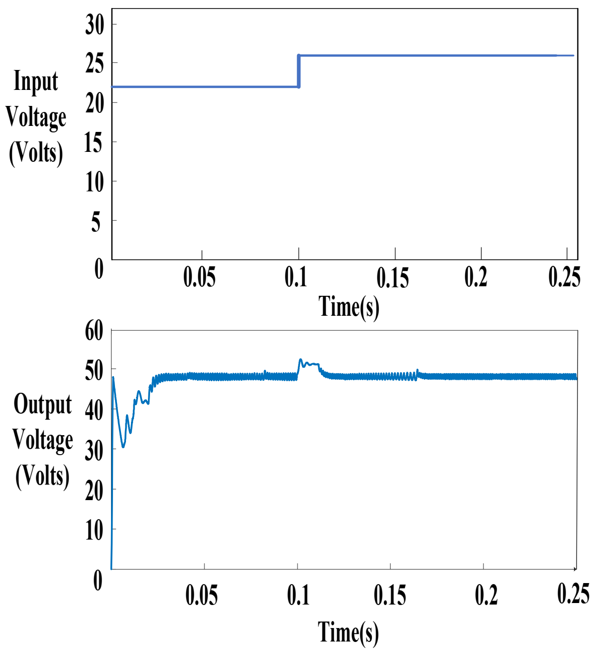


**Figure 11**.Voltage waveforms for PI controller

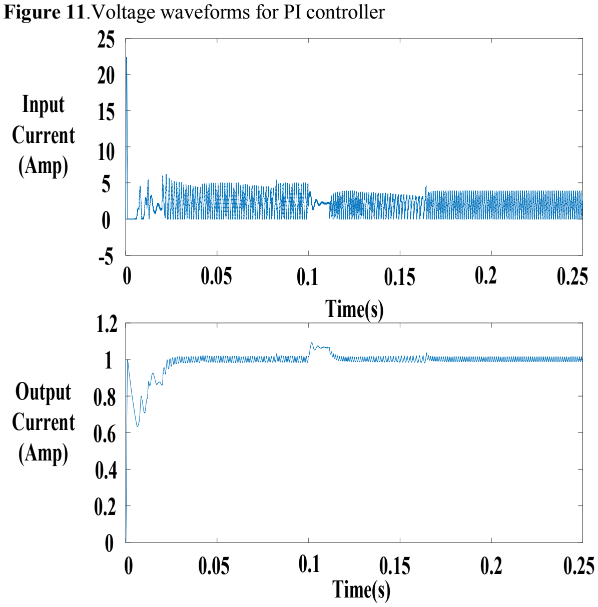


**Figure 12**. Current waveforms for PI controller

**TABLE 2**- SPECIFICATION FOR BOOST CONVERTER

| Parameters | Symbol | Values |
|---|---|---|
| Input voltage disturbance range | $v_i$ | 22-26 V |
| Input voltage | $V_i$ | 24 V |
| Desired output voltage | $V_o$ | 48 V |
| Inductance | L | 0.3mH |
| Capacitance | C | 230 µF |
| Switching frequency | $f_s$ | 200kHz |
| Inductor parasitic resistance | $r_L$ | 0.13 Ω |
| Capacitance ESR | $r_c$ | 0.069 Ω |
| Minimum load resistance | $R_{(min)}$ | 48 Ω |
| Maximum load resistance | $R_{(max)}$ | 240 Ω |

**TABLE 3** – COMPARISON OF SM CONTROL AND PI CONTROLLER IN PARAMETER

| Parameter | SMC | PI |
|---|---|---|
| Settling time, $t_s$ | 0.006 s | 0.5 s |
| Rise time, $t_r$ | 0.003 s | 0.04 s |
| Ripple in output voltage, $V_{ripple}$ | 0.4 V | 4 V |
| Ripple in inductor current, $I_{L,ripple}$ | 0.01 A | 0.8 A |

In Fig. 9 and Fig. 10 it is shown that when some disturbance come in input side, output voltage is not disturbed. It is shown when input voltage is varying from 24 volt to 22 volt at 0.5 s output voltage is not varying so much and it is maintained at 48 volt which is the desired voltage. Input current or inductor current is also almost constant which is the desired feature of any input supply to give supply. In this work both controllers are tested for load disturbance also and it is verified through MATLAB results that SM controllers have robust nature for disturbance.

In Fig. 11 and Fig. 12 it is shown that when disturbance is given in input side, output voltage of boost converter with PI controller is varying so much with high ripples and input current and output current have very high ripples which is not desired feature of any controller. A comparison analysis is done with results of MATLAB simulation in TABLE 3.So that a clear understanding view can be made for desired features as such fast response, wide operating range, robust feature for disturbances, steady state error and transient response.

Table-3 shows that settling time, rise time, output voltage ripples and current ripples for SM controller are less compared to PI controller. Hence indirect SM current controller is a better choice for controlling action of switching power converters.

## VI. CONCLUSION

SM is a very impelling control approach and it has many advantages such as high robustness, reduced order compensated dynamics, high simplicity, inherent stability, finite time convergence, etc.., In this paper at a fixed frequency PWM based indirect SM current controller and PI controller for non- isolated boost converter are simulated in MATLAB/SIMULINK. Results show that SM current controller has faster response, stable transient response and refused load and input disturbances, less output ripples as compared to only current mode control, only voltage mode control and PI controllers also. In industries PI controllers are used due to its simplicity and less cost but desired characteristics are not so adequate. Where as non-linear SM control technique is used in automotive and furnace control.

Future work of this SM control scheme will be extended for DC μ-grid and also robotics, where hybrid energy storage is and vital aspect. The system can be realized by hardware using D-Space 1104.

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