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# Sliding Mode Control of Three-Phase Grid connected Photovoltaic System

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***Abstract*— This paper deals with a photovoltaic system connected to a grid. Sliding Mode Control is used for the maximum power extraction from the photovoltaic array by dc-dc boost converter and for the conversion of dc bus voltage to three-phase ac voltage by three-phase inverter and injection of generated power from the photovoltaic system directly to utility grid.**

***Index Terms*—Sliding Mode Control, photovoltaic system, dc-dc boost converter with MPPT, three-phase grid**

## I. INTRODUCTION

Renewable energy has more importance today when compared with the other form of energy generation because of depleting fossil fuel reserves and also these traditional fuels and nuclear power are not eco-friendly. Among the renewable energy solar energy has wide importance all over the world. As the solar energy can be converted by photovoltaic arrays to electrical energy and can be used at different location where as other renewable energy systems cannot.

Several control strategies for grid connected photovoltaic system have been developed [3], [4], [5], [6], [7] and [8]. commonly consists of a dc-dc boost converter with MPPT technique to extract maximum power from the photovoltaic array and then followed by a dc-ac converter to interface the power between the photovoltaic system and utility grid. A LCL filter is used at the inverter before integrating the power to grid to remove any harmonics present in the output of the inverter

## II. PV SYSTEM MODELING

The proposed system of three-phase grid connected photovoltaic system is as shown in fig 1.

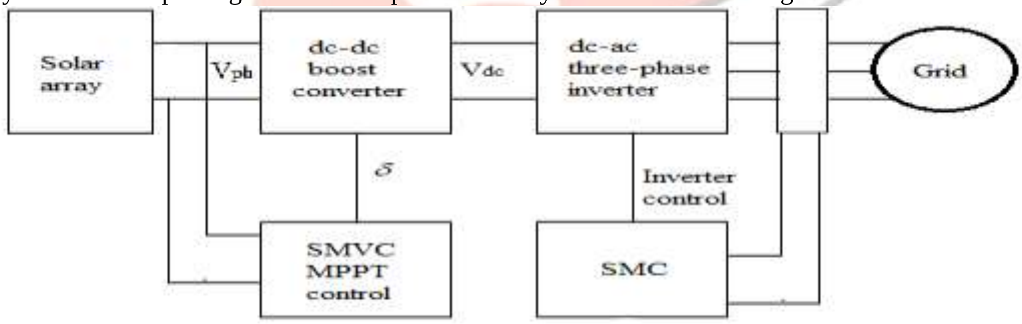


Fig 1. Block of grid connected photovoltaic system

A number of series and parallel combination of solar modules to generate the required power output. While making an PV array, generally the modules are connected initially in series manner to obtain the desired voltage, and in parallel to produce more current based on the requirement. A boost converter is used to raise the generated dc voltage, and to extract the maximum power from the PV. Three-phase full-bridge inverter converts the dc voltage into sinusoidal voltage.

### A. PV CELL MATHEMATICAL MODELING

Consider a two diode model [9] of PV cell as shown in fig 2.

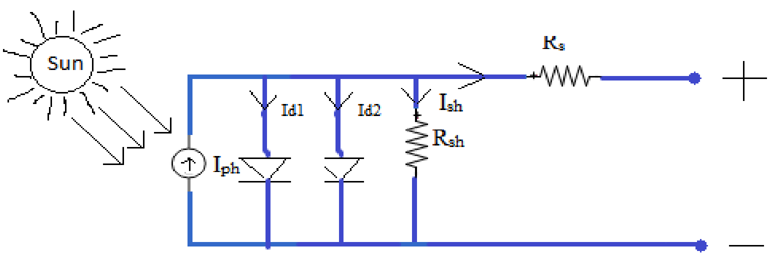


Fig 2 Two diode PV model

The mathematical equation for this model is as represented in equation 1.

$$I = I_{ph} - I_{s1}\{e^{v_d q/n_1 KT} - 1\} - I_{s2}\{e^{v_d q/n_2 KT} - 1\} - \frac{V + IR_s}{R_{sh}} \quad (1)$$

where $I_{ph} = \{I_{ph\_STC} + \alpha_{sc}\Delta T\}\dfrac{G}{G_{STC}}$ , generated current equation

$I_{s_{1,2}} = I_{S\_STC}\left(\dfrac{T_{STC}}{T}\right)^3 \exp\left[\dfrac{qE_g}{aK}\left(\dfrac{1}{T_{STC}} - \dfrac{1}{T}\right)\right]$, reverse saturation current

$I_{s\_STC} = \dfrac{\left(I_{SC\_STC} + K_v\Delta T\right)}{\exp\left(\dfrac{V_{oc\_stc} + k_v\Delta T}{\alpha_{sc}V_T}\right) - 1}$ , saturation current under STC

$I_{S\_STC}$ - Saturation current at STC

$E_g$ - Energy band gap for semiconductor

T – Temperature

$T_{STC}$ - Temperature at STC

$q$ - Charge of electron

$I_{SC\_STC}$ - short circuit current at standard test condition

$V_{oc\_stc}$ - open circuit voltage at standard test condition

$k_v$ - Temperature coefficient of open circuit voltage

a - Diode ideality constant

As the total power generated by a single PV cell is very low, we used a combination of PV cells to fulfill our desired requirement, with $N_s$ series and $N_{sh}$ shunt diodes as PV array as shown in fig 3.

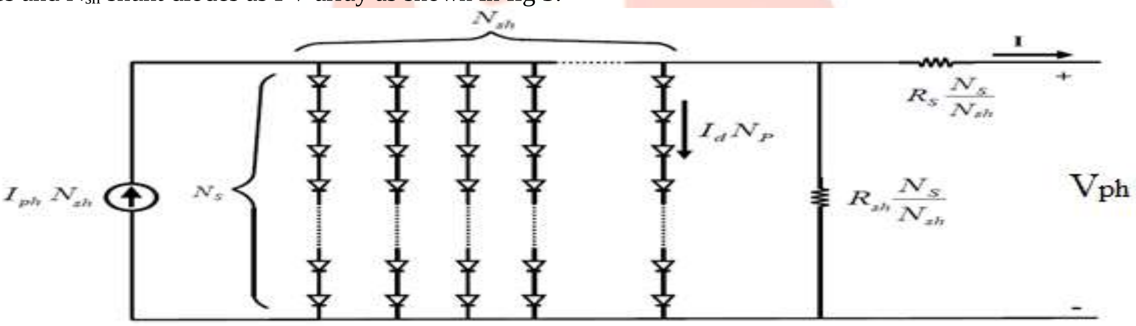


Fig 3. PV model with $N_s$ series and $N_{sh}$ shunt diodes and its equivalent series resistance and parallel resistance.

The equation of PV array is given by

$$I = I_{ph}N_{sh} - I_sN_{sh}\left[\exp\left(\frac{V + IR_s\left(\frac{N_s}{N_{sh}}\right)}{a_1V_TN_s}\right) + \exp\left(\frac{V + IR_s\left(\frac{N_s}{N_{sh}}\right)}{a_2V_TN_s}\right) - 2\right] - \frac{V + IR_s\left(\frac{N_s}{N_{sh}}\right)}{R_{sh}\left(\frac{N_s}{N_{sh}}\right)} \quad (2)$$

B. **BOOST CONVERTER**

Boost converter [12] is used to raise the PV voltage to the desired level and also to track the MPP from the PV array. Block diagram of boost converter is as shown in fig 4.

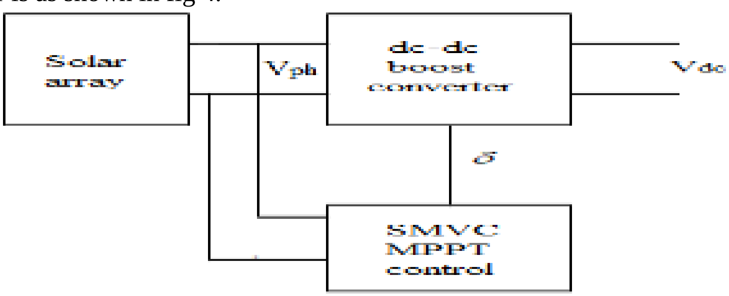


Fig 4. Boost converter block diagram

State equations of dc-dc boost converter [10] is given as

$$L_{pv}\frac{di_{pv}}{dt}=v_{pv}-R_{lpv}\times I_{lpv}-v_{dc}(1-\delta) \quad (3)$$

$$C\frac{dv_c}{dt}=\frac{-v_c}{R_c}+\left(\frac{i_{lpv}}{R_c}\right)(1-\delta) \quad (4)$$

$$v_{dc}=v_c+i_c\times R_c \quad (5)$$

where current through capacitor is given by $i_c=(1-\delta)i_{lpv}$ to extract the maximum power from PV array sliding mode voltage controller(SMVC) is implemented.

### C. THREE-PHASE INVERTER MODELING WITH LCL FILTER

Three-phase VSI's are used to interface between dc and ac systems in distributed power generation system. The model of grid connected PV system as shown in fig 1.

The equations for grid connected inverter is given by [8], [1]

$$v_{dc}\left(s_1-s_2\right)=v_{an}+v_{no} \quad (6)$$

$$v_{dc}\left(s_3-s_4\right)=v_{bn}+v_{no} \quad (7)$$

$$v_{dc}\left(s_5-s_6\right)=v_{cn}+v_{no} \quad (8)$$

Where $s_1$ to $s_6$ are transistors acts as switches

The model equations for three-phase inverter in matrix form is given as

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix}=\frac{v_{dc}}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}$$

where $f_1$ to f3 are PWM signals

The average model of three-phase VSI with LCL filter is as shown in fig 6.

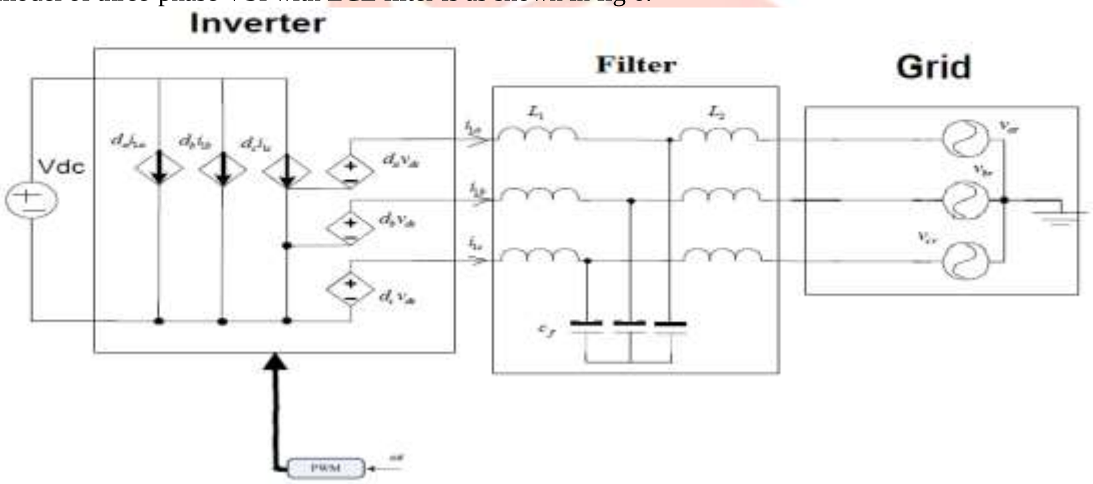


Fig 6. Average VSI circuit model

Current equations for $L_1$

$$L_1\left[\frac{di_{l1a}}{dt}\right]=\left[v_{an}\right]-\left[v_{cfa}\right] \quad (9)$$

$$L_1\left[\frac{di_{l1b}}{dt}\right]=\left[v_{bn}\right]-\left[v_{cfb}\right] \quad (10)$$

$$L_1\left[\frac{di_{l1c}}{dt}\right]=\left[v_{cn}\right]-\left[v_{cfc}\right] \quad (11)$$

Voltage equations for $C_f$

$$c_f\left[\frac{dv_{cfa}}{dt}\right]=\left[i_{l1a}\right]-\left[i_{l2a}\right] \quad (12)$$

$$c_f\left[\frac{dv_{cfb}}{dt}\right]=\left[i_{l1b}\right]-\left[i_{l2b}\right] \quad (13)$$

$$c_f\left[\frac{dv_{cfc}}{dt}\right]=\left[i_{l1c}\right]-\left[i_{l2c}\right] \quad (14)$$

Current equations for $L_2$

$$L_2\left[\frac{di_{l2a}}{dt}\right]=\left[v_{cfa}\right]-\left[v_{ar}\right] \tag{15}$$

$$L_2\left[\frac{di_{l2b}}{dt}\right]=\left[v_{cfb}\right]-\left[v_{br}\right] \tag{16}$$

$$L_2\left[\frac{di_{l2c}}{dt}\right]=\left[v_{cfc}\right]-\left[v_{cr}\right] \tag{17}$$

abc to dq0 transformation is given by

$$\begin{bmatrix}u_d\\u_q\\u_0\end{bmatrix}=\frac{2}{3}\begin{bmatrix}\cos(\omega t) & \cos\left(\omega t-\frac{2\pi}{3}\right) & \cos\left(\omega t+\frac{2\pi}{3}\right)\\ -\sin(\omega t) & -\sin\left(\omega t-\frac{2\pi}{3}\right) & -\sin\left(\omega t+\frac{2\pi}{3}\right)\\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2}\end{bmatrix}\begin{bmatrix}u_a\\u_b\\u_c\end{bmatrix} \tag{18}$$

Applying abc to dq transformation to equations (9) to (17)

We have

$$\begin{bmatrix}\dot{i}_{L1d}\\ \dot{i}_{L1q}\end{bmatrix}=\frac{1}{L_1}\left[\begin{bmatrix}v_d\\v_q\end{bmatrix}-\begin{bmatrix}v_{cfd}\\v_{cfq}\end{bmatrix}-\frac{3}{2}\omega L_1\begin{bmatrix}-i_{L1q}\\ i_{L1d}\end{bmatrix}\right] \tag{19}$$

$$\begin{bmatrix}\dot{v}_{cfd}\\ \dot{v}_{cfq}\end{bmatrix}=\frac{1}{C_f}\left[\begin{bmatrix}i_{L1d}\\i_{L1q}\end{bmatrix}-\begin{bmatrix}i_{L2d}\\i_{L2q}\end{bmatrix}-\frac{3}{2}\omega C_f\begin{bmatrix}-v_{cfd}\\ v_{cfq}\end{bmatrix}\right] \tag{20}$$

$$\begin{bmatrix}\dot{i}_{L2d}\\ \dot{i}_{L2q}\end{bmatrix}=\frac{1}{L_2}\left[\begin{bmatrix}v_{cfd}\\v_{cfq}\end{bmatrix}-\begin{bmatrix}v_{dr}\\v_{dq}\end{bmatrix}-\frac{3}{2}\omega L_2\begin{bmatrix}-i_{L2q}\\ i_{L2d}\end{bmatrix}\right] \tag{21}$$

The instantaneous active and reactive power which is delivered to the grid line in dq rotating frame is given by

$$P=\frac{2}{3}v_{dr}i_{L2q} \tag{22}$$

$$Q=\frac{2}{3}v_{qr}i_{L2d} \tag{23}$$

## III. PROPOSED CONTROLLERS

### 1. MPPT CONTROL

There are various control techniques for the MPPT control [10]. We study the SMC control of MPPT technique [2]. The control function for MMPT is assumed to be a non-linear integral control and can be expressed in matrix form as

$$x=\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}=\begin{bmatrix}v_{ref}-\beta v_{dc}\\ \frac{d\left(v_{ref}-\beta v_{dc}\right)}{dt}\\ \int\left(v_{ref}-\beta v_{dc}\right)dt\end{bmatrix} \tag{24}$$

where $x_1$ is error voltage

$x_2$ is voltage error dynamics

$x_3$ is integral of voltage error

For CCM of inverter, equation (24) can be modified as

$$\dot{x}_{boost}=\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & \frac{-1}{r_l C} & 0\\ 1 & 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}+\begin{bmatrix}0\\ \frac{\beta v_{dc}}{LC}-\frac{\beta v_{ph}}{LC}\\ 0\end{bmatrix}\bar{u} \tag{25}$$

where $\bar{u}=1-u$ is the inverse logic of $u$

SMC based MPPT control schematic diagram as shown in fig 7.

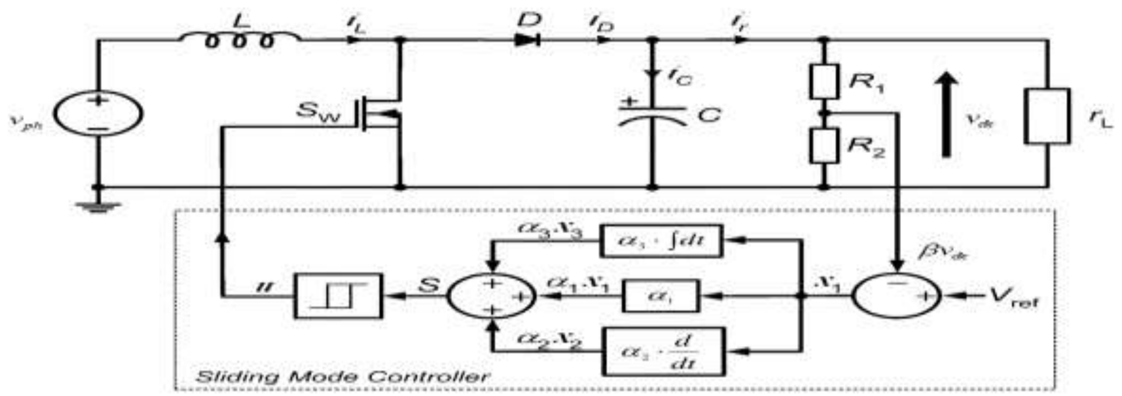

Fig 7. MPPT SMC control

The state space form of equation (25) in standard form $\dot{x} = Ax + Bu + D$

Where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \frac{-1}{r_l C} & 0 \\ 1 & 0 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ \frac{\beta v_{dc}}{LC} - \frac{\beta v_{ph}}{LC} \\ 0 \end{bmatrix} \quad (26)$$

$$D = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

For these systems, it is appropriate to have a general SM control law that adopts a switching function such as

$$u = \begin{cases} 1, & \text{when } S>0 \\ 0, & \text{when } S<0 \end{cases} \quad (27)$$

Where S is the instantaneous state variable's trajectory, and is described as

$$S = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 = J^T x \quad (28)$$

Where $J^T = [\alpha_1 \quad \alpha_2 \quad \alpha_3]$

$\alpha_1$, $\alpha_2$ and $\alpha_3$ are the control parameters termed as sliding coefficients

(a) **DERIVATION OF EXISTANCE CONDITION**

The existence conditions of SMC operation the local reachability condition $\lim_{S \to 0} S.\dot{S} < 0$ must be satisfied

For boost converter

$$-\alpha_1 \frac{\beta i_C}{C} + \alpha_2 \frac{\beta i_C}{r_l C^2} + \alpha_3 (v_{ref} - \beta v_{dc}) < 0 \quad (29)$$

$$0 < \beta L \left( \frac{\alpha_1}{\alpha_2} - \frac{1}{r_{l(\min)} C} \right) i_{C(SS)} - LC \frac{\alpha_1}{\alpha_2} \left( v_{ref} - \beta v_{dc(SS)} \right) < \beta (v_{dc(SS)} - v_{ph(\max)}) \quad (30)$$

We have taken into account the complete ranges of operating conditions (minimum and maximum input voltages, i.e., $v_{dc(\min)}$ and $v_{dc(\max)}$, and minimum and maximum load resistances, i.e., $r_{l(\min)}$ and $r_{l(\max)}$. This assures the compliance of the existence condition for the full operating ranges of the converters. In the case of designing an SM controller with a static sliding surface, a practical approach is to design the sliding coefficients to meet the existence conditions for steady-state operations. Under such consideration, the state variables $i_C$ and $V_{dc}$ can be substituted with their expected steady-state parameters, i.e., $i_{C(SS)}$ and $v_{dc(SS)}$, which can be derived from the design specification.

(b) **SELECTION OF SLIDING COEFFICIENTS**

The equation relating the sliding coefficients to the dynamic response of the converter during SM operation can be easily found by solving S=0, which results in a linear second-order equation with three possible types of responses: under-damped $(0 \le \zeta < 1)$, critically damped $(\zeta = 1)$, and over-damped $(\zeta > 1)$. In the case of under-damped response converters, the desired settling time $(\zeta > 1) T_s = 5\tau s$ (1% criteria), where is the natural time constant, can be set by tuning $\frac{\alpha_1}{\alpha_2}$ using

$$\frac{\alpha_1}{\alpha_2} = \frac{10}{T_s} \tag{31}$$

And the desired damping ratio can be set using

$$\frac{\alpha_3}{\alpha_2} = \frac{25}{\zeta^2 T_s^{\,2}} \tag{32}$$

Where $\zeta = \sqrt{\dfrac{\left[In\left(\dfrac{M_p}{100}\right)^2\right]}{\pi^2 + \left[In\left(\dfrac{M_p}{100}\right)^2\right]}}$

And $M_p$ is the % peak over shoot.

(c) **DERIVATION OF CONTROL EQUATION FOR PMW-BASED CONTROLLER**

The equivalent control function is mapped onto the instantaneous duty cycle function of the pulse width modulator for boost converter

$$v_c = -K_{p1} i_C + K_{p2}\left(v_{ref} - \beta v_{dc}\right) + \beta(v_{dc}) \tag{33}$$

And $\hat{v}_{ramp} = \beta(v_{ph})$ (34)

Where

$$K_{p1} = \beta L\left(\frac{\alpha_1}{\alpha_2} - \frac{1}{r_L C}\right)$$
$$K_{p2} = \frac{\alpha_3 LC}{\alpha_2} \tag{35}$$

The values of $K_{p1}$ and $K_{p2}$ can be found in terms of converter's parameters L, C and $r_L$ .

2. **THREE PHASE INVERTER CONTROL**

The SMC control for three-phase inverter [11], Let the reference currents that are to be injected to the controller is given by

$$i_{L2q}^{\ *} = \frac{2}{3V_{rd}} P^* \tag{36}$$

$$i_{L2d}^{\ *} = \frac{2}{3V_{rq}} Q^* \tag{37}$$

where $P^*, Q^*$ are reference active and reactive power, $i_{L2q}^{\ *}, i_{L2d}^{\ *}$ are reference currents

Let the error functions be

$$e_1 = i_{L2d} - i_{L2d}^{\ *} \tag{38}$$

$$e_2 = i_{L2q} - i_{L2q}^{\ *} \tag{39}$$

Let the control for the non-linear system be $c_1 e_1 + c_2 \dot{e}_1 + \ddot{e}_1 = 0$ (40)

where $c_1, c_2, c_3$ are positive constants

we have the control law third derivatives of equations (38), (40) as

$$\dddot{e}_1 = \dot{i}_{L2d}\left[\frac{1}{C_f L_2} + \frac{9}{4}\omega^2\right] - \frac{3}{2}\frac{\omega}{L_2}\dot{V}_{cfq} - \frac{1}{C_f L_2 L_1} V_d + \frac{1}{C_f L_2 L_1} V_{cfd} - \frac{3}{2}\frac{\omega}{C_f L_2} i_{L1q} \tag{41}$$

$$\dddot{e}_2 = \dot{i}_{L2q}\left[\frac{1}{C_f L_2} + \frac{9}{4}\omega^2\right] + \frac{3}{2}\frac{\omega}{L_2}\dot{V}_{cfd} - \frac{1}{C_f L_2 L_1} V_q + \frac{1}{C_f L_2 L_1} V_{cfq} + \frac{3}{2}\frac{\omega}{C_f L_2} i_{L1d} \tag{42}$$

The control vectors $V_d$ and $V_q$ are in the third derivative of error functions. By exponential reaching law let the surfaces of the SMC can be written as

$$\dot{s}_1 = -Ms_1 - Nsign(s_1) \tag{43}$$

$$\dot{s}_2 = -Ms_2 - Nsign(s_2) \tag{44}$$

From equations (43), (44) and (41), (42) we have the control law as

$$V_d = C_f L_2 L_1 \left[ Ms_1 + Nsign(s_1) + \dot{i}_{L2d} \left[ \frac{1}{C_f L_2} + \frac{9}{4}\omega^2 \right] - \frac{3\omega}{L_2}\dot{V}_{cfq} + \frac{V_{cfd}}{C_f L_2 L_1} - \frac{3}{2}\frac{\omega}{C_f L_2} i_{L1q} \right] \tag{45}$$

$$V_q = C_f L_2 L_1 \left[ Ms_2 + Nsign(s_2) + \dot{i}_{L2q} \left[ \frac{1}{C_f L_2} + \frac{9}{4}\omega^2 \right] + \frac{3\omega}{L_2}\dot{V}_{cfd} - \frac{V_{cfd}}{C_f L_2 L_1} + \frac{3}{2}\frac{\omega}{C_f L_2} i_{L1d} \right] \tag{46}$$

Where

$$M_1 = M_2 = \frac{2}{3V_{rq}}, \; B_1 = B_2 = C_f L_2 L_1$$

$$A_2 = \dot{i}_{L2d} \left[ \frac{1}{C_f L_2} + \frac{9}{4}\omega^2 \right] - \frac{3\omega}{L_2}\dot{V}_{cfq} + \frac{V_{cfd}}{C_f L_2 L_1} - \frac{3}{2}\frac{\omega}{C_f L_2} i_{L1q} \tag{47}$$

$$A_1 = \dot{i}_{L2q} \left[ \frac{1}{C_f L_2} + \frac{9}{4}\omega^2 \right] + \frac{3\omega}{L_2}\dot{V}_{cfd} - \frac{V_{cfd}}{C_f L_2 L_1} + \frac{3}{2}\frac{\omega}{C_f L_2} i_{L1d} \tag{48}$$

Block diagram for the proposed control is as shown in fig 8.

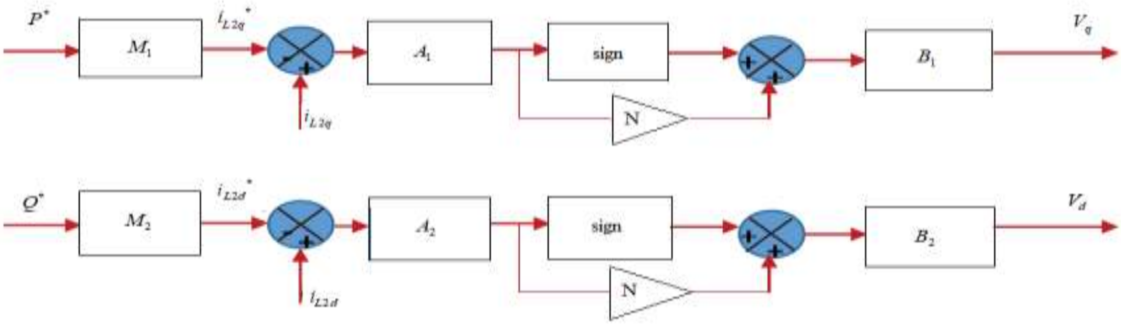


Fig 8. Block diagram of SMC

## IV. RESULTS

The Figure below gives the characteristic I-V and P-V curve for fixed level of solar irradiation and temperature for a Sun Power SPR-305E-WHT-D with parallel cells $N_{sh}$ =11, series cells $N_s$ =3 Power developed by solar array= $305 \times 11 \times 3 = 10065$ Watt

Table 1 CHARACTERISTICS OF SUN POWER SPR-305E-WHT-D

| ***Parameter*** | ***value*** | ***Parameter*** | ***value*** |
|---|---|---|---|
| Maximum power | 305.266 | Shunt resistance(ohms) | 270 |
| Open circuit voltage(V) | 64.2 | Series resistance(ohms) | 0.4 |
| Voltage at MPPT(V) | 54.7 | Temperature coefficient of Isc(%$^0$C) | 0.061745 |
| Cells per module | 96 | Light generated current(A) | 6 |
| Current MPPT(A) | 5.58 | Short-circuit current(A) | 5.96 |

PV and IV characteristic curves for the PV array is as shown below fig 9.

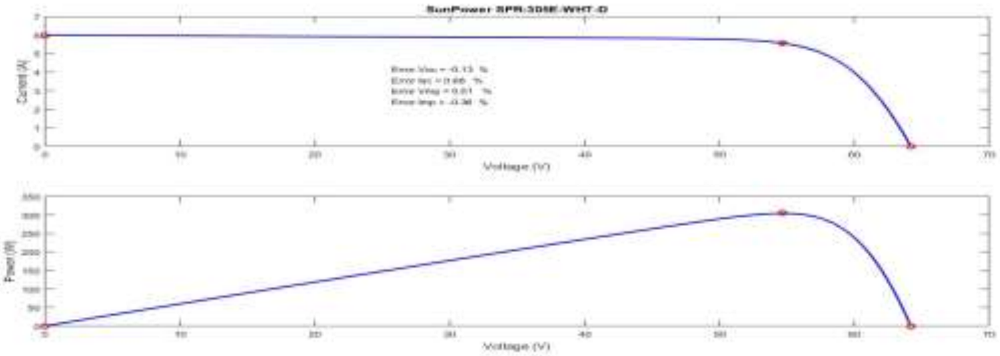


Fig.9. PV, IV Characteristics curves for solar array at fixed temperature 35$^0$C and irradiance 1000Wb/m$^2$

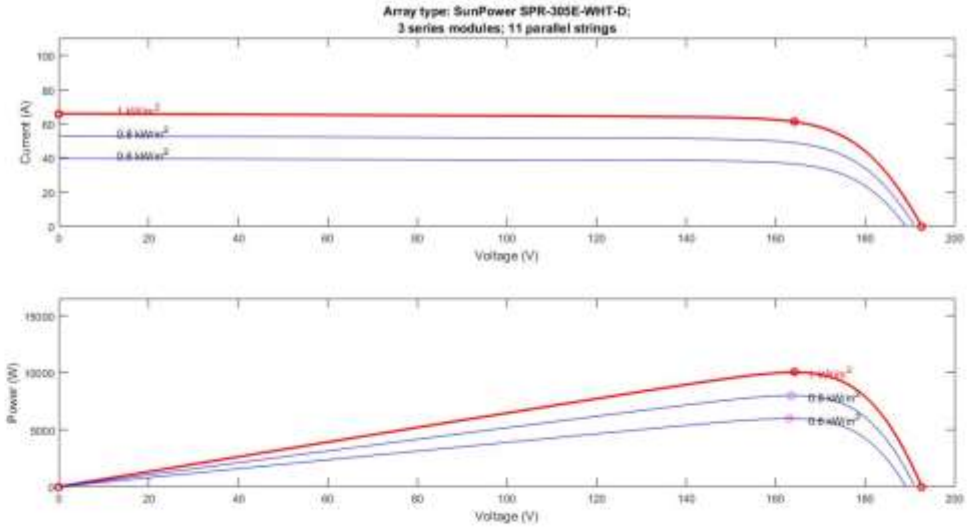


Fig. 10 PV, IV Characteristics curves for solar array at fixed temperature 25$^0$C and different irradiance at 1000 Wb/m$^2$, 800 Wb/m$^2$, 600 Wb/m$^2$

Fig. 10 illustrate as the irradiance of light decreases the power and current generated by PV array decreases. MPPT also varies

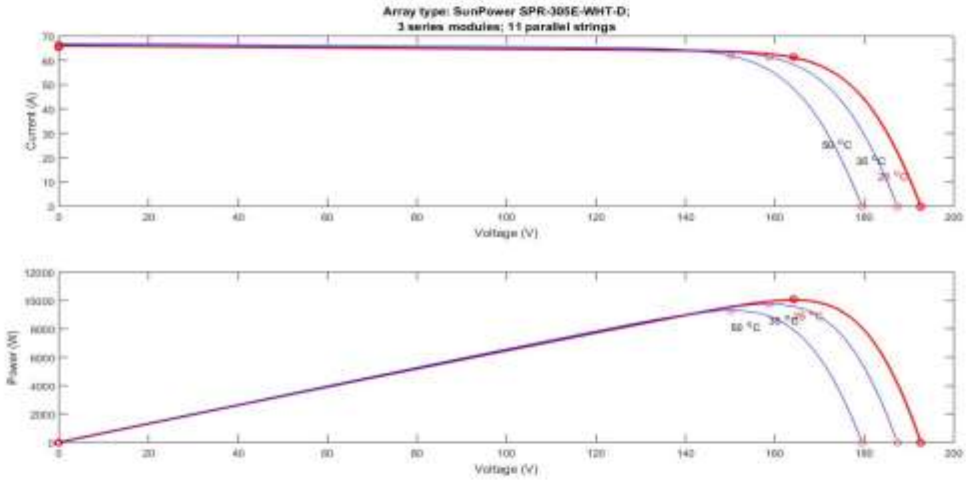


Fig .11 PV, IV Characteristics curves for solar array at fixed irradiance and variable temperature

Fig. 11 illustrate as the temperature varies MPPT and Vsc varies at constant irradiance

Fig. 12 illustrate the output voltage of the PV array

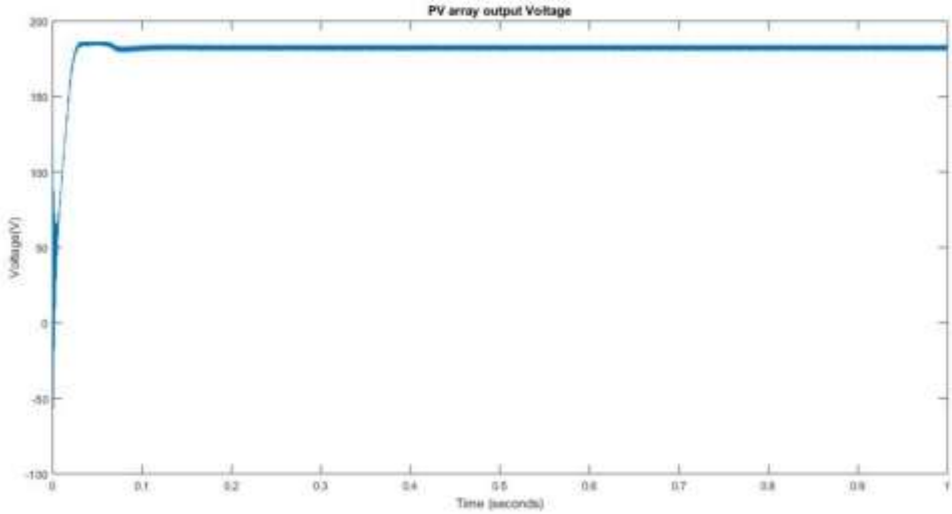


Fig 12 PV array output voltage

Fig.13 illustrate the boost up voltage of the PV array by SMC control reached the steady state voltage of 500V and a constant voltage level is maintained over the time.

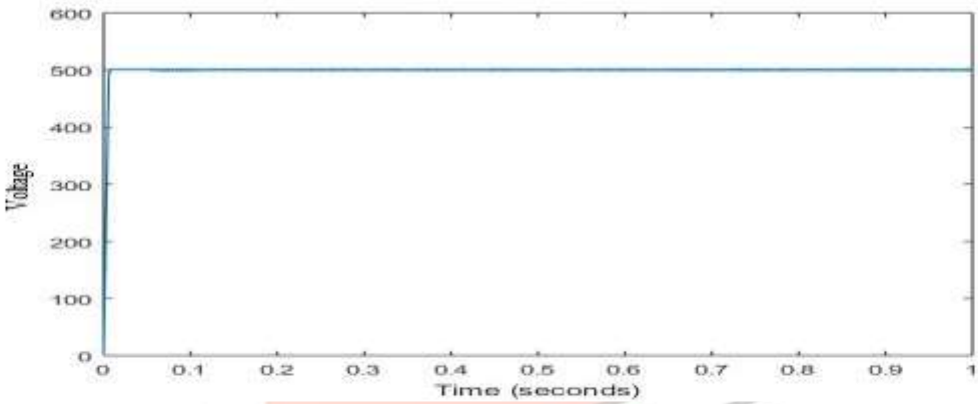


Fig. 13 Output voltage of boost converter

Fig. 14 illustrate the output voltage of the dc-ac, three-phase inverter. The proposed controller converts the dc voltage to three-phase voltage to the reference voltage. Voltage level is adjusted to reference voltage by the controller before 0.1sec.

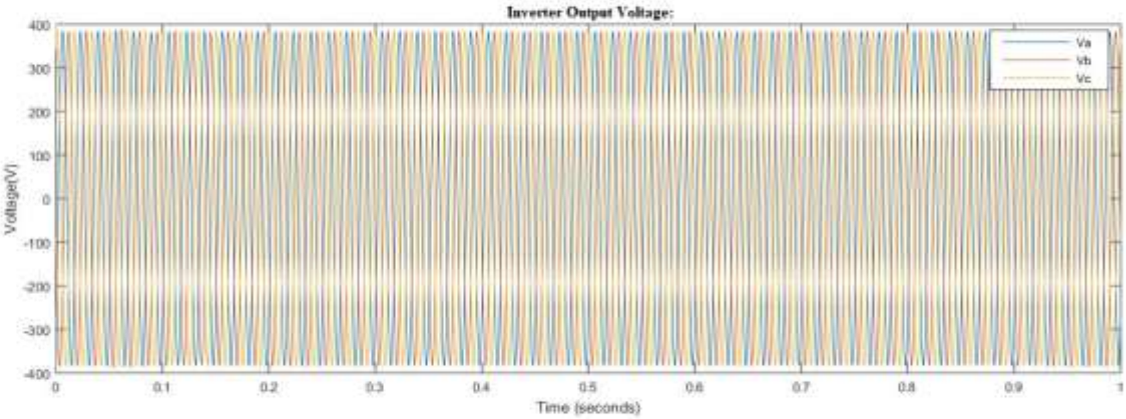


Fig.14 Output voltage of the three-phase inverter

Fig.15 illustrate the grid voltage. The voltage of the three-phase inverter is stepped up to the grid voltage by a three-phase transformer.

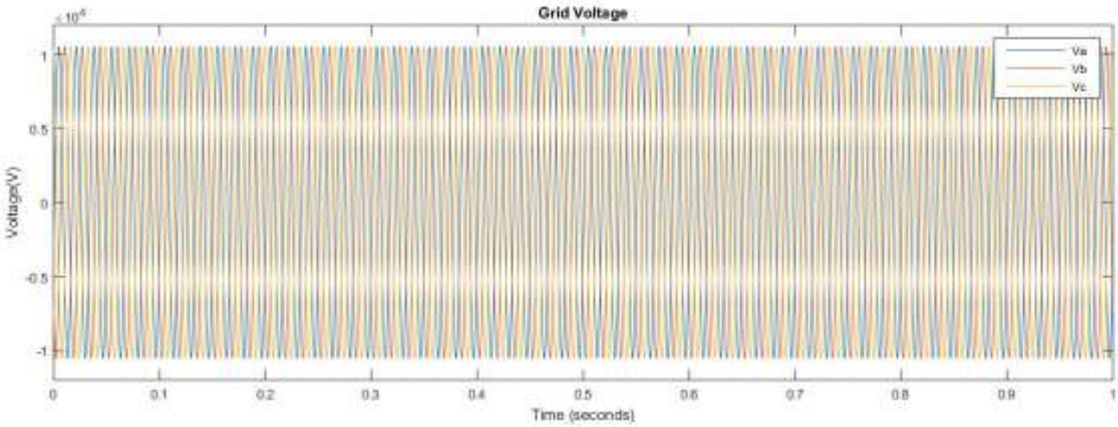


Fig.15 Grid voltage

Fig. 16 illustrate the injected currents. The LCL filter filters the harmonics in the current waves. The injected currents reach the steady state current levels at 0.1sec.

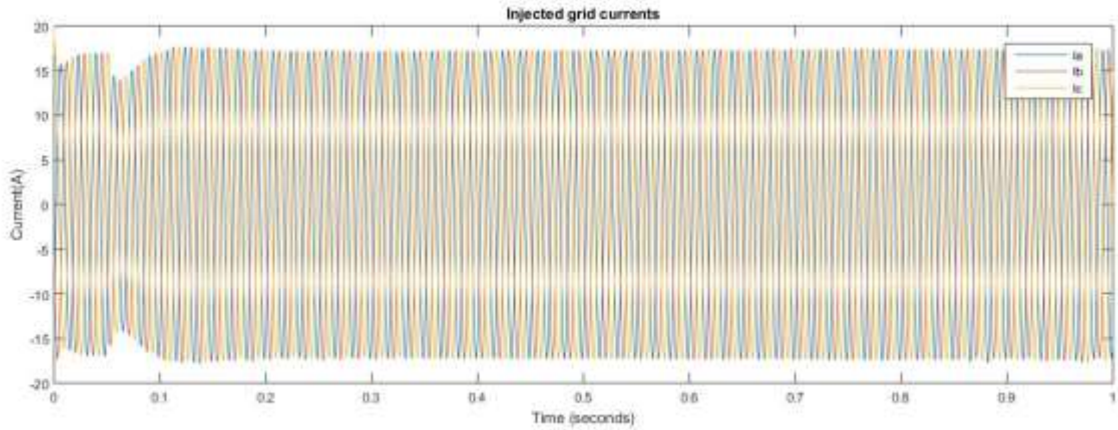


Fig.16 Injected currents in to grid

## V. CONCLUSION

In this paper a grid connected three-phase inverter model is simulated by MATLAB. Dc-dc boost converter for extraction of maximum power by proposed SMC is satisfactory and the results are plotted. Dc-ac three-phase inverter converts the dc bus voltage to three-phase voltages by proposed SMC controller and the voltage levels are maintained at the reference levels. The performance of the SMC controller for three-phase inverter is satisfactory and the results of the three-phase inverter are plotted.

**Abbreviations**

| | | |
|---|---|---|
| PV | : | Photovoltaic |
| PVG | : | Photovoltaic generator |
| MPPT | : | Maximum Power Point Tracking |
| MPP | : | Maximum Power Point |
| $I_{ph}$ | : | Photovoltaic cell current |
| $I_{ph\_STC}$ | : | Photovoltaic cell current at STC |
| STC | : | Standard Test Condition |
| $I_d$ | : | Diode Current |
| $V_d$ | : | Diode Voltage |
| q | : | Charge of electron |
| n | : | Ideality factor |
| K | : | Boltzmann constant |
| T | : | Temperature |
| $I_{s1,2}$ | : | Diode reverse saturation current |
| $I_{S\_STC}$ | : | Diode reverse saturation current at STC |
| $R_s$ | : | Series resistance |

| | | |
|---|---|---|
| $R_{sh}$ | : | Shunt resistance |
| $\alpha_{sc}$ | : | Short-circuit current coefficient |
| $G$ | : | Irradiance |
| $G_{STC}$ | : | Irradiance at STC |
| $T_{STC}$ | : | Temperature at STC |
| $E_g$ | : | Energy gap |
| $N_{sh}$ | : | Shunt diodes |
| $N_s$ | : | Series diodes |
| $\delta$ | : | Duty cycle |
| $f_s$ | : | Switching frequency |
| $v_{an}, v_{bn}, v_{cn}$ | : | Output voltage of inverter |
| $v_{no}$ | : | Neutral voltage |
| $f_{res}$ | : | Resonance frequency |
| $v_d$ , $v_q$ | : | Direct and quadrature axis voltages |
| $v_{cfa}, v_{cfb}, v_{cfc}$ | : | Voltage of filter capacitance |
| $v_{ar}, v_{br}, v_{cr}$ | : | Voltage of the grid |
| $i_{l2a}, i_{l2b}, i_{l2c}$ | : | Injected grid currents |
| $\zeta$ | : | Damping ratio |
| $T_s$ | : | Settling time |
| $M_p$ | : | %peak over shoot |
| PWM | : | Pulse Width Modulation |
| $u_{eq}$ | : | Control signal |
| $K_{p1}$, $K_{p2}$ | : | Constant gain parameters |
| $\beta$ | : | Ratio of $v_{ref}$ to $v_{dc}$ |
| $i_{L2q}^*$ | : | Quadrature axis reference current |
| $i_{L2d}^*$ | : | Direct axis reference current |
| $e_1$ , $e_2$ | : | Error currents |

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