Design of Sliding Mode Controller for Three Phase Grid Connected Photovoltaic System

D. Kalyanraj*, S. Lenin prakash and M. Arutchelvi

Abstract: Design and implementation of constant frequency sliding mode current control for grid connected Photovoltaic (PV) inverter is presented along with Maximum Power Point Tracking (MPPT). Proposed constant frequency sliding mode control retains the advantages of good dynamic response as in hysteresis control, better reference tracking capability and robustness like predictive control. Proposed current controller has the advantages in constant switching frequency and less sensitivity to parameter variations. Grid current harmonics complies with IEEE 1547 and has been achieved in a simpler means when compared to other existing techniques.

Keywords: Sliding mode; current control; PV inverter; grid tied.

1. INTRODUCTION

In recent years the requirement of renewable energy has become more vital. Due to the exhaustion of fossil energy, increasing fuel price, climatic changes, improvements in semiconductor technology and environmental contamination, forced the use of renewable energies such as photo voltaic (PV) system and wind power system for a few decades. The PV energy is environmental friendly, free of cost, abundant and spread through the earth. PV systems can be subdivided into two large categories 1. Standalone systems 2. Grid connected systems. Standalone system is mostly adopted with battery for energy storage and control of such systems are not much complex when compare to the grid tied systems. Standalone PV systems are not a complete solution for today energy demand, to meet the energy demand large amount of PV energy has to be connected to the grid. The purpose of PV-grid integration is to transfer maximum PV power to the grid with unity power factor and minimum current THD, this is mainly relays on the high efficiency power electronics converters mostly choppers and inverters. Control of such PV inverters are not much simpler like standalone PV inverter. Mostly PV energy is connected to the grid through the following two topologies 1. PV energy directly connected to inverter DC link 2.PV energy is first fed to the DC chopper then inverter DC link. Single stage grid integration as in topology 1 requires large number of PV panels to get the required voltage level also this topology is very sensitive to variations in solar irradiation. Two stage PV-grid integration as in topology 2 requires less number of PV panels and chopper gives the opportunity to get the desired voltage levels with better power control. PV inverter and its control circuit play a vital role in proper and safety operation of PV-Grid tied systems. These inverters require high performance current controllers to exactly track the reference current as well as to reduce the current harmonics to ensure safety operation of whole system. Hysteresis and predictive current controllers are most popular current control techniques used for PV inverters. In Hysteresis control switching frequency is not constant even though works [1-2] gives the methods to make the switching frequency constant that increases complexity in implementation. Predictive control provides constant switching frequency but it needs accurate information

Saranathan college of engineering (Anna University), Trichy-620 012, Tamilnadu,, India
* e-mail: kalyanrajeee@gmail.com

about the circuit parameters [3]. Objective of this paper is to propose a constant frequency sliding mode current controller for PV inverter with high degree of accuracy in tight regulation of grid current and reduced current harmonic distortion. This paper is structured as follows; section 2 explains the typical configuration of proposed sliding mode current controlled PV-grid system. In section 3, complete design procedure of constant frequency sliding mode controller for grid tied PV inverter system is presented. In section 4, simulation of PV-Grid system with proposed current control is presented. Performance of the proposed controller is validated with the results of inverter performance indices like THD, steady state error, phase plane trajectory etc has also been presented in section 4. Conclusions from the simulation results were presented in section 5.
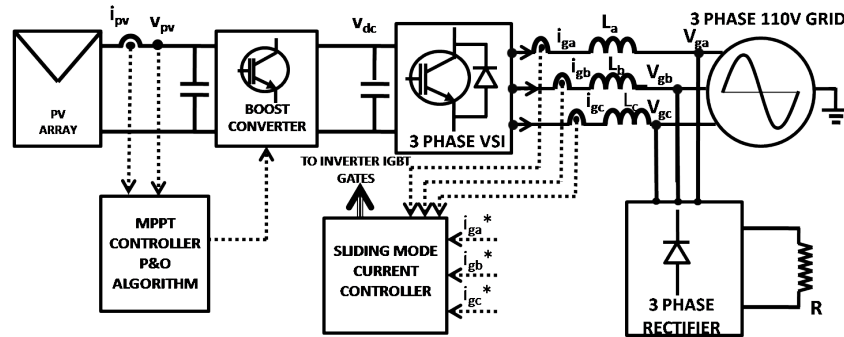

Figure 1: Power circuit and control circuit block diagram of proposed grid tied system.

2.   CONFIGURATION OF PROPOSED THREE PHASE GRID TIED PV SYSTEM

Fig. 1 shows the complete configuration of proposed PV-grid tied system with sliding mode control. This consist of PV array, MPPT controller, Boost converter, Linking capacitor, three phase inverter, interfacing inductor, sliding mode current controller and three phase non-linear load (rectifier fed resistive load). To get maximum power from the Photovoltaic array most popular Perturb and observe (P&O) MPPT algorithm is implemented. This method is characterized by introducing a small variation in power by decreasing or increasing the PV voltage, after this alteration once again power is measured and compared with the previous value. If the present power is greater than the previous power (before alteration) means operating point is moved closer to the Maximum Power Point (MPP). So the next alteration is introduced into the system same direction as previous case to move the operating point towards the MPP. If the present power (after alteration) is less than the previous power then next alteration is introduced in opposite direction to reach MPP. This process is continued until it reaches steady state value (MPP).The boost chopper is used to make the alteration of the operating voltage of the PV array. In P&O method reference voltage is generated by sensing the PV voltage and current. Linear PI controller is used to control the PV array voltage by tracking the reference voltage generated by P&O algorithm. PI controller gives better regulation of PV voltage by appropriately switching the boost chopper. In PV-grid tied systems inverter plays a crucial role, performance of whole system is largely depends on the inverter and its associated control circuitry. Interfacing inductors are used to synchronize the inverter output voltage and grid. In this present work sliding mode current control is proposed for inverter switching for the tight regulation of grid current with reduced current harmonics. The sliding mode controller is very robust and it is not sensitive to any kind of circuit parameter fluctuations unlike predictive control[3].In most of the past research works, sliding mode control is only used for PV boost converters as voltage controller or current controller[4-5]. A non linear three phase diode bride rectifier is connected at point of common coupling(PCC) to validate the proposed controller performance in terms of tracking capability and harmonic rejection. Total PV system is connected to 110V grid.

3. DESIGN OF CONSTANT FREQUENCY SLIDING MODE CURRENT CONTROLLER AND INTERFACING INDUCTOR

Sliding mode control is a type of discontinuous control which is developed for the control of variable structure systems. In sliding mode control operating point moves through or moves within the sliding surface, which is achieved with the help of some control inputs. So selecting the appropriate sliding surface (SF) or sliding manifold is first step in designing the controller. It is very conventional to choose sliding surface as the di□erence between the state variables and their references. By this for the present grid tied PV system sliding manifold can be chosen with errors of the PV array voltage and grid current. MPPT controller gives the DC solar array reference voltage, inductor current or grid current can be get by using current sensors. Due to the sinusoidal nature of inductor current, it is very difficult to maintain the PV array voltage constant. Due to this oscillating nature of PV array voltage, sliding mode control is not suitable for a grid connected photo voltaic system [3,6]. This can be overcome by selecting the SF only in terms of inductor current and its reference current alone.Design of sliding mode current control involves two control inputs other than sliding surface 1. Equivalent control input 2. Non linear switching input.

Selection of a sliding manifold or sliding surface

ζ (x,t) =0 (reference current –inductor or grid current=0)

Equivalent control input u_{equ} is obtained by the invariance condition,

$\zeta(x,t)=0$ And $\dot{\zeta}(x,t)=0$ with $u(t)=u_{equ}$ The existence of the equivalent control $u_{equ} i(t)$ maintains the operating point within the sliding surface $\zeta(x,t)=0$.

Nonlinear control input u_{non} is obtained by using Lyapunov stability criteria, i.e. $\zeta \dot{\zeta} < 0$.

The proposed sliding surface is given by,

$$\zeta(x,t)=I_{ga}-I_{ref} \tag{1}$$

The power supplied to the grid is given by,

$$P_g = V_{ga}(t)I_{ga} + (I_{ga})^2 R$$

By assuming negligible resistance R≈0,

$$P_g = V_{ga}(t)I_{ga} \tag{2}$$

Where,

$$I_{ga} = I_{ga\_pk}\sin \omega t \tag{3}$$

$$V_{ga}(t) = V_{GP}\sin \omega t \tag{4}$$

Substitute (3) & (4) in (2)

$$P_g = I_{ga} * V_{ga}(t) = V_{GP}I_{ga\_pk}\sin^2 \omega t$$

$$= V_{GP}I_{ga\_pk}(1-\cos 2\omega t)/2 \tag{5}$$

Where , I_{ga_pk} = peak current of A phase grid current; V_{GP} = peak of $V_{ga}(t)$

Average grid power is obtained by integrating P_E,

$$P_{g\_avg} = 2/T \int (V_{GP}I_{ga\_pk}(1-\cos 2\omega t)/2)dt = V_{GP}I_{ga\_pk}/2 \tag{6}$$

Assuming lossless power transmission from inverter input to grid,

$$P_{dc\_avg} = P_{g\_avg} = V_{GP}I_{ag\_pk}/2 \tag{7}$$

Using (7),

$$I_{ga\_pk} = 2P_{dc\_avg} / V_{GP} \tag{8}$$

Reference current becomes,

$$I_{ref} = 2P_{dc\_avg} \sin \omega t / V_{GP} \tag{9}$$

$$I_{ref} = I_{ga}* = I_{gb}* = I_{gc}* $$

Total control input u(t) is preferred by,

$$u(t) = u_{equ}(t) + u_{non}(t) \tag{10}$$

Where $u_{equ}(t)$ is an equivalent control input that controls the behavior on the SF and $u_{non}(t)$ is a non-linear switching input, which forces the operating point towards the sliding surface and maintains the operating point within the sliding surface. Invariance condition is used to obtain the $u_{equ}(t)$. (η - noise and measurement error)

$$I_{ga} = \int ([V_{dc}u(t) - RI_{ga} - V_{ga}(t)] / L_n) + \eta \tag{11}$$

$$L_n = L_a = L_b = L_c$$

From (1), (9) & (11), $\dot{\zeta}(x,t) = (V_{dc}u_{equ}(t) - RI_{ga} - V_{ga}(t)) / L_n - 2P_{dc\_avg} \cos \omega t / V_{GP} = 0 \tag{12}$

From that, the equivalent control input is given as,

$$u_{equ}(t) = (RI_{ga} + V_{ga}(t) + 2P_{dc\_avg}L_n \omega t / V_{GP}) / V_{dc} \tag{13}$$

Non- linear control input $u_{non}(t)$ is obtained by Lyapunov stability criteria, i.e. $\zeta \dot{\zeta} < 0$.

$$u_{non}(t) = -\alpha \operatorname{sgn}(\zeta) \tag{14}$$

Using (1) & (12) $\zeta \dot{\zeta} = \zeta(\dot{I}_L - (2P_{dc\_avg}\omega \cos \omega t) / V_{GP}) \tag{15}$

Differentiating (11) and substitute in (15)

$$\zeta \dot{\zeta} = \zeta((V_{dc}[u_{equ}(t) + u_{non}(t)] / L_n) - E_{ga}(t) / L_n + \eta - (2P_{dc\_avg}\omega \cos \omega t) / V_{GP}) \tag{16}$$

Substitute in $u_{equ}(t)$ & $u_{non}(t)$ in (16)

$$= \zeta(-V_{dc}\alpha \operatorname{sgn}(\zeta) / L_n + \eta) < 0 \tag{17}$$

The range of switching gain(α) is given by

$$\alpha = (L_n * \eta) / V_{dc}$$

Hence $u(t)$ is given by,

$$= \frac{RI_{ga} + E_{ga}(t) + 2PL_n\omega \cos \omega t / V_{GP} - \eta L_n \operatorname{sgn}(\zeta)}{V_{dc}} \tag{18}$$

Inverter is switched such that to track the reference current by comparing the total control input u(t) with the pulse width modulated triangular voltage.

From fig.2, To determine the factors that influence the inverter switching frequency, let one phase of the grid be described by the differential equation (19).
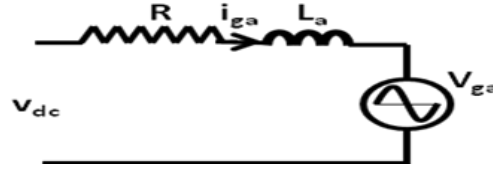
Figure 2: Eqiuvelent circuit of one phase of the grid(A phase)

From fig. 2,

$$V_{dc} = RI_{ga} + L_a dI_{ga} / dt + V_{ga} \tag{19}$$

Where,

V_{dc} = Inverter DC link voltage; I_{ga} = A phase grid current, V_{ga} = A phase grid voltage,

R   = Resistance, L_a = A phase interfacing Inductance.

The time Δt in which the current will increase by Δi can be found using (19) assuming that the resistance is negligible.

$$L_a \Delta i / \Delta t = V_{dc} - V_{ga}$$

$$\Delta t = L_a \Delta i / V_{dc} - V_{ga}$$

$$2\Delta t = T \text{ (Total time period)}$$

Switching frequency, $fs = (Vdc - V_{ga}) / 2L_a \Delta i$.

$$L_a = (Vdc - V_{ga}) / 2 fs \ \Delta i \tag{20}$$

4. SIMULATION AND RESULTS OF CONSTANT FREQUENCY SLIDING MODE CURRENT CONTROL

In this section simulation of PV-Grid integration with proposed sliding mode current controlled three phase inverter along with MPPT control has been presented. Simulated power circuit of complete PV-Grid integration system is shown in fig. 3. MPPT control (P&O) is implemented for boost converter along with the PI controller. To test the performance of proposed controller a non linear load (3 phase diode bridge rectifier) is connected at PCC. Parameters considered for simulation are V_{dc}=440V, f =50hz, R=5Ω, fs =10Khz,L_a =16.5mH, I_{ref} is changed from 5A to 4A, per phase grid voltage is 110V. For PV array V_{oc} =310V, I_{sc}= 8.1A, V_{ref} in MPPT controller considered is 282V.
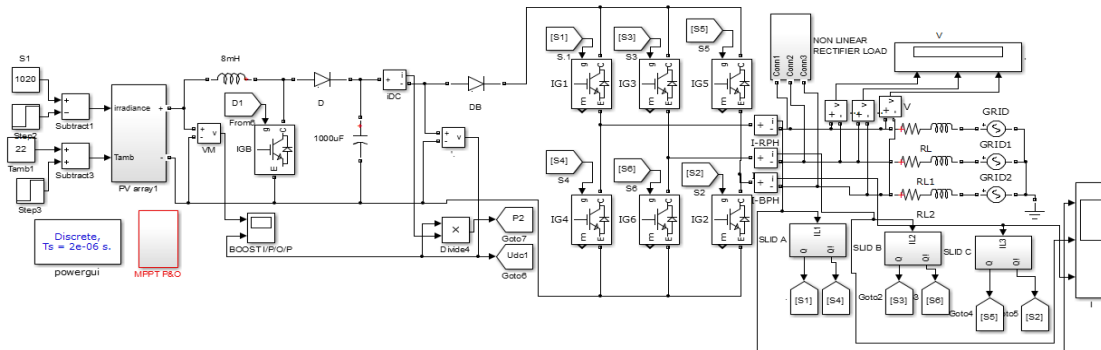

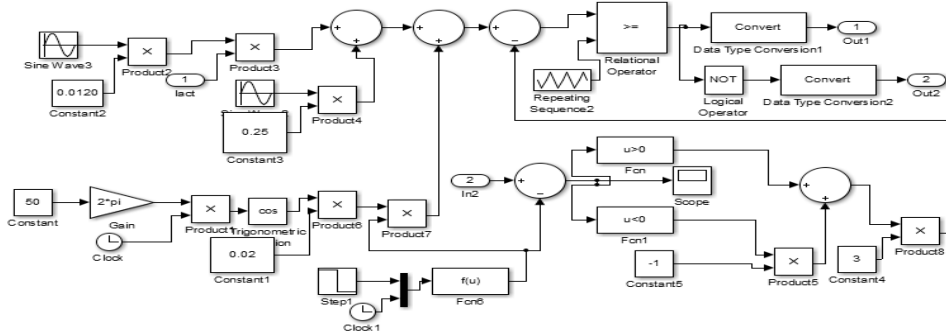**Figure 3: Simulated power circuit of proposed PV-grid system**

Figure 4: Proposed constant frequency sliding mode controller (A phase)

Total control input u(t) of sliding mode controller is obtained by substituting the known values of circuit parameters into the equation (18)

Using (18 and 20), $\quad u(t) = 0.0120I_L \sin \omega t + 0.25 \sin \omega t + 0.02I_{ref} \cos \omega t - 3\,\text{sgn}(\sigma)$ $\qquad$ (21)

Eqn (21) is implemented in matlab simulink and the simulated sliding mode controller is shown in fig 4
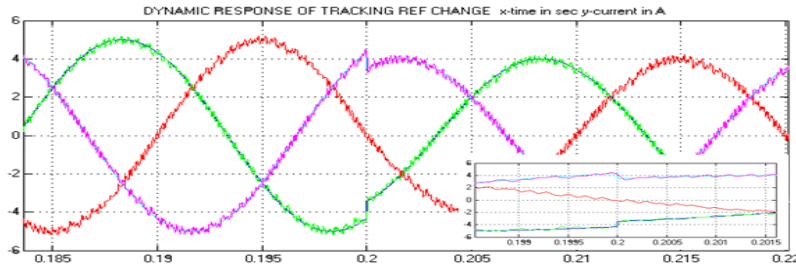

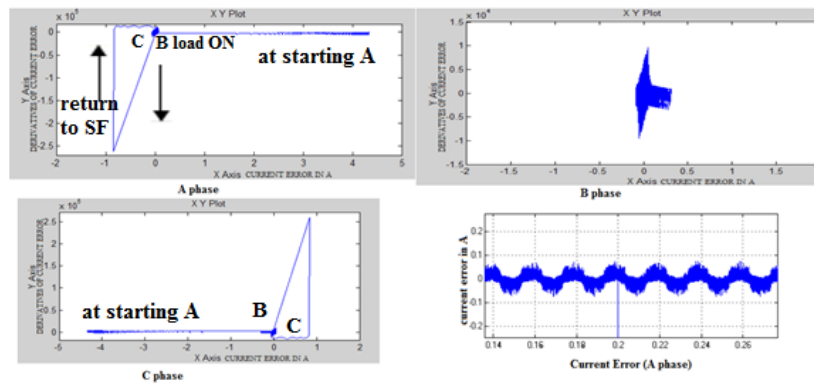**Figure 5: Three phase grid currents tracks the reference current change from 5A to 4A**

Figure 6: Phase plane trajectory of sliding mode current controller along with steady state current error
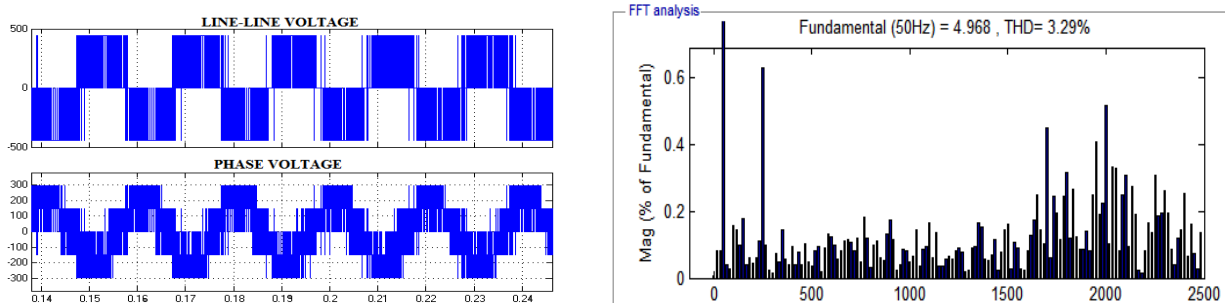

Figure 7 (a): current harmonic spectrum grid current(R phase) (b) line and phase voltage of PV inverter

Fig 5 shows the three phase grid currents follows the reference current change from 5A to 4A with high degree of accuracy. Sliding mode current control tracks the change in reference current in 0.1ms which proves the dynamic response of the proposed current control strategy. Steady state error of the proposed current control is shown in fig. 6 it is around 0.1A which proves the accuracy of sliding mode control. Phase Plane Trajectory is the finest approach to study the response of the different controllers under different disturbance conditions. Phase Plane trajectory is usually plot between the current error and derivatives of current error. Phase plane trajectory of sliding mode control is shown in fig. 6. At the time of starting current is nearly 4A, non linear control input forces the current error to the SF to track the reference current. At point B, Rectifier load is switched ON; Actual current goes outside the SF. Within a millisecond, current error again forced to SF and also maintained within SF with the help of equivalent control input. This is due to the sudden introduction of non-linear load in to the grid.fig. 7(a) shows the harmonic spectrum of A phase grid current, the current THD is 3.29% complying with the 5% limit of IEEE 1547. Inverter line and phase voltages also shown in fig 7(b)

5. CONCLUSIONS

Constant frequency sliding mode current control for grid connected PV inverter system has been presented.

The main conclusions are as follows:

(1) From the simulation results it has been proved that proposed current controller has good dynamic response, better reference tracking capability,(2) minimum steady state error(0.1A), (3) Reduced current harmonic distortion(3.29%) complying with IEEE 519 and IEEE 1547, (4) Constant switching frequency unlike hysteresis control, (5) This controller not sensitive to circuit parameter variations, Robust,(6) high degree of disturbance rejection capability, (7) sliding mode controller doesn't require exact circuit parameters unlike predictive controller, (8) simple implementation.

References

[1]   Carl Ngai-Man Ho Victor S.P.Cheung,, and Henry Shu-Hung Chung," Constant-frequency hysteresis current control of grid-connected VSI without bandwidth control," *IEEE T Power Electr.,* Vol 24, pp. 2484-2495,2009.

[2]   Ching-Tsai Pan, Yi-Shuo Huang, and Che-Ying Li," An error bounded current controller with constant sampling frequency," *IEEE T Power Electr.,*Vol 19, pp. 739-747, 2004.

[3]   Song Kim. Sliding mode controller for the single-phase grid-connected photovoltaic system. *Applied energy*, Elsevier, Vol 83, pp.1101-1115, 2006.

[4]   Domingo Cortes, Nimrod Vázquez, Jaime Alvarez-Gallegos, "Dynamical Sliding-Mode Control of the Boost Inverter," *IEEE T Ind electr,* vol. 56, pp. 3467-3476, 2009.

[5]   A. Etxeberria,I. Vechiu, H. Camblong, J.-M. Vinassa," Comparison of Sliding Mode and PI Control of a Hybrid Energy Storage System in a Microgrid Application," *Energy Procedia,*Vol.12, pp. 966-974, 2011.

[6]   C.Edwards and S.K.Spurgeron, "Sliding Mode Control: Theory and Applications," London,U.K.: Taylor and Francis,1998.

[7]   Song Kim, "Robust maximum power point tracker using sliding mode controller for the three-phase grid-connected photovoltaic system," *Solar energy,* Elsevier Vol.81, pp. 405-414, 2007.