CHAPTER 4

FINITE TIME SLIDING MODE POWER CONTROL OF GRID CONNECTED THREE-PHASE PHOTOVOLTAIC ARRAY
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4.1 Introduction

This chapter presents active and reactive power control of a three-phase grid-connected photovoltaic generation system, using a new control approach for the voltage source converter (VSC). Instead of controlling the direct- and quadrature-axis currents of the VSC, the instantaneous real-and reactive power components are used as control variables. This mode of control dispenses the unmodeled dynamics of the VSC phase-locked loop (PLL) system and produces a robust control for the active-, reactive power, and dc voltage excursions. Further the stability of the grid connected PV array is enhanced by designing a Lyapunov function based finite time nonlinear reactive power and dc link voltage controller, which essentially uses the terminal sliding mode approach. Comprehensive computer simulations are carried out in MATLAB/SIMULINK to verify the robustness of the proposed approach under several system disturbances, like changes in solar insolation and active and reactive power references, islanding conditions, converter parametric changes, and faults on the converter and inverter buses. In all these cases the new controller is found to enhance overall system stability in comparison to the inferior performance by the proportional-integral (PI) controller.

This chapter is organized in five sections. After the introduction in Section-4.1, Section-4.2 presents a detailed PV system model followed by dynamic model and PI
control of VSC in Section-4.3. Lyapunov function based Sliding Mode controller of VSC models is discussed in Section-4.4. Several test cases and the simulation results that include short-circuits, power mismatches between the load and PV generation, islanding, and power reference changes, etc. are presented in Section-4.5 to highlight the superior performance of the new approach. This section also provides a MATLAB/SIMULINK (Sim power system tool box) validation of the proposed control during transient changes. Lastly concluding remarks are given in Section-4.6.

4.2 PV SYSTEM MODEL

The basic element of any PV system is the PV cell. Number of PV cells connected in series-parallel is in general treated as a PV array. A more approximated but relatively accurate model for a PV panel, with \( n_p \) number of parallel cells and \( n_s \) number of series cells, the current-voltage characteristic function can be given by (4.1).

\[
i_{pv} = n_p I_{ph} - n_p I_{rs} \left[ \exp \left( \frac{q V_{dc}}{k T} \right) - 1 \right]
\]  

(4.1)

where \( \Theta \) is the working temperature of the cell, \( V_{dc} \) is the output voltage, \( I_{rs} \) is the reverse saturation current of a p-n junction and \( i_{pv} \) is the output current of PV array, \( k \) is the Boltzmann’s constant. The cell reverse saturation current is expressed as

\[
I_{rs} = i_{rr} \left( \frac{\Theta}{\Theta_{ref}} \right)^2 \exp \left( \frac{q E_G}{k A} \left[ \frac{1}{\Theta_{ref}} - \frac{1}{\Theta} \right] \right)
\]  

(4.2)

where \( \Theta_{ref} \) the reference temperature of the PV cell is, \( E_G \) is the cell band-gap energy, and \( i_{rr} \) is the reverse saturation current at the reference temperature.

The photovoltaic current, \( I_{ph} \) and power output, and the power \( P_{pv} \) delivered by the PV are given as follows:
\[ I_{ph} = 0.01 [I_{sc} + K_f (T - T_{ref})] S = \beta S \]  

(4.3)

where \( I_{sc} \) is the short-circuit current of the PV array at the reference temperature \( T_{ref} \) and solar irradiance, \( K_f \), and \( S \) are temperature coefficient and insolation level in kW/m\(^2\), respectively.

\[ P_{pv} = V_{dc} * i_{pv} = n_p I_{ph} V_{dc} - n_p I_{rs} V_{dc} \left[ \exp \left( \frac{q V_{dc}}{k \beta A n_s} \right) - 1 \right] \]

\[ = n_p \beta S V_{dc} - n_p I_{rs} V_{dc} \left[ e^{\alpha V_{dc}} - 1 \right] \]  

(4.4)

where

\[ \alpha = \frac{q}{k \beta A n_s} \quad q = 1.602 \times 10^{-19} \quad \text{Boltzmann’s constant} \quad k = 1.38 \times 10^{-23} \text{J/K} \]

\( A \)=ideality factor. From equation (4.4) it can be seen \( P_{pv} \) is a function of the insolation level directly and the dc voltage \( V_{dc} \), indirectly. The change in PV panel power for a small change in solar insolation is obtained as

\[ \frac{dP_{pv}}{dV_{dc}} = n_p \beta S - n_p I_{rs} (e^{\alpha V_{dc}} + \alpha V_{dc} e^{\alpha V_{dc}} - 1) \]  

(4.5)

In order to clamp the dc voltage at a certain level, the maximum power point tracking algorithm (MPPT) [63] for the PV panels is used as shown in Fig.4.1 for a typical PV system for insolation levels of 600W/m\(^2\), 800W/m\(^2\) and 1000W/m\(^2\), respectively. The maximum power extracted from the PV array is 6.37 kW, 8.66 kW and 10.98 kW at dc-link voltage of 234.3 V, 238.6 V and 241.9 V respectively.
Equating $dP_{pv} / dV_{dc} = 0$, the maximum power extracted from the PV array at a solar insolation $S_0$ can be obtained by solving the nonlinear equation (4.6) after obtaining $V_{dc0}$

$$(e^{\alpha V_{dc0}} + \alpha V_{dc0} e^{\alpha V_{dc0}} - 1) = \beta S_0 / I_{rs} \tag{4.6}$$

Fig. 4.1. Variation of PV power with insolation at constant temperature

Fig. 4.2 shows that for an isolated PV system, when the load is withdrawn, the PV array supplies 0 W power at dc-link voltage of 282.624V for 800W/m$^2$ solar irradiation.

Fig. 4.2. PV System characteristic
4.3 Development of VSC model for Power Control

A three-phase bidirectional DC-AC IGBT based voltage source converter using PWM modulation technique is used as the inverter interface between the PV array and the grid. The traditional control scheme for active and reactive power flowing from the converter to the grid is based on the control of the instantaneous direct- and quadrature-axis components of current. A PLL is used to generate the direct- and quadrature axis currents from the measured line currents in the abc frame of reference. If the PLL dynamics is unmodeled, the control system must be robust to take care of the unaccounted PLL dynamics. Recently an alternative approach [62] has been suggested where instantaneous active- and reactive-power components are chosen as dynamic variables, rather than conventional d-q currents components. Thus to calculate the active and reactive power flows from the converter a phase frame of reference is used to measure the phase or line voltages and currents. Fig. 4.3 shows a schematic diagram of the PV system interfaced with a distribution system at PCC through a VSC and an interface of impedance \( R_i + j\omega_i L_i \); where \( \omega_i \) is the power system angular frequency. The impedance of the line segment between PCC and the grid is \( R_g + j\omega_g L_g \). An RLC load is connected at the PCC.

The dynamic model of VSC in abc reference frame is

\[
V_{abc} = L_p i_{abc} + R_i i_{abc} + V_{abc} \quad (4.7)
\]

where \( p = d/dt \) (differential operator)
Equation (4.7) can be transformed in the $d$-$q$ reference frame as

$$p_{i_d} = -\frac{R}{L} i_d + \omega e i_{iq} + \frac{V_{id} - V_{sd}}{L} \tag{4.8}$$

$$p_{i_q} = -\frac{R}{L} i_{iq} - \omega e i_d + \frac{V_{iq} - V_{sq}}{L} \tag{4.9}$$

where the inverter voltages in the d-and q-axis are obtained as

$$V_{id} = \frac{mV_{dc} \cos \delta}{\sqrt{2}}, V_{iq} = \frac{mV_{dc} \sin \delta}{\sqrt{2}}, \tag{4.10}$$

where $m$ and $\delta$ are the PWM modulation index and firing angles for the VSC inverter.

Further the dynamics of the DC link capacitor voltage is given by

$$\frac{1}{C} \frac{dV_{dc}^2}{dt} = P_{pv} - P_{dc}, \text{ and } P_{dc} = P_t + P_{loss} \tag{4.11}$$

Where $P_{dc}$ the power is delivered to the VSC dc side and $P_t$ is the active power from the inverter bus. Neglecting the VSC power loss, $P_{dc}$ is equal to $P_t$.
Again instantaneous active and reactive power at the PCC in $dq$-reference frame is expressed as

\[
P_i = (3/2)(V_{sd}i_{sd} + V_{sq}i_{sq}), \quad Q_i = (3/2)(V_{sq}i_{sd} - V_{sd}i_{sq})
\]  
(4.12)

The instantaneous currents in $dq$ reference frame at PCC are obtained as

\[
i_{sd} = \frac{2}{3} \left( \frac{PV_{sd} + QV_{sq}}{V_s^2} \right) i_{sq} = \frac{2}{3} \left( \frac{PV_{sq} - QV_{sd}}{V_s^2} \right)
\]  
(4.13)

, and

\[
V_s^2 = V_{sd}^2 + V_{sq}^2
\]

The voltage components $V_{sd}, V_{sq}$ and $i_{sd}, i_{sq}$ active and reactive powers $P_i, Q_i$ are obtained from the phase voltage and current components in the stationary frame [62] as

\[
V_{sd} = (1/\sqrt{3})(V_{sb} - V_{sc}), i_{sd} = (1/\sqrt{3})(i_{sb} - i_{sc})
\]

\[
V_{sq} = (2/3)V_{sa} - (1/3)(V_{sb} + V_{sc}),
\]

\[
i_{sq} = (2/3)i_{sa} - (1/3)(i_{sb} + i_{sc})
\]

\[
P_i = \frac{3}{2} (V_{sd}i_{sd} + V_{sq}i_{sq}) = (V_{sa}i_{sa} + V_{sb}i_{sb} + V_{sc}i_{sc})
\]

\[
Q_i = \frac{3}{2} (V_{sq}i_{sd} - V_{sd}i_{sq}) = \frac{1}{\sqrt{3}} [V_{sa}(i_{sb} - i_{sc}) + V_{sb}(i_{sc} - i_{sa}) + V_{sc}(i_{sa} - i_{sb})]
\]

Substituting the values of $i_{sd},$ and $i_{sq}$ from equation (4.13) to equations (4.8) and (4.9), the following differential equations are obtained for the active and reactive power flows from the PCC as
\[
\frac{dP_i}{dt} = -\frac{R_i}{L_i} P_i - \omega_e Q_i + \frac{3}{2L_i} \left( (V_{sd} V_{sd} + V_{sq} V_{sq}) - (V_{sd}^2 + V_{sq}^2) \right) \quad (4.15)
\]

\[
\frac{dQ_i}{dt} = -\frac{R_i}{L_i} Q_i + \omega_e P_i + \frac{3}{2L_i} \left( V_{sq} V_{sd} - V_{sd} V_{sq} \right) \quad (4.16)
\]

The dynamic equation of the DC voltage for the VSC is given by Eq.(4.17)

\[
\frac{dV_{dc}}{dt} = \frac{1}{CV_{dc}} (P_{pv} - P_{dc}) \quad (4.17)
\]

where \( P_{dc} \) is the VSC dc side power. Neglecting the VSC power loss, the following equation is obtained:

\[
P_{dc} = P_i \quad (4.18)
\]

and \( P_i \) is the VSC ac-side active power.

In most of the conventional control schemes for voltage source converters, PI based current controllers are used. Although they are structurally simple and offer fast dynamics and zero steady state error, their performance deteriorates when the operating conditions change. However, the extensive range of applications of PI-based current regulation strategies need to be considered for comparison with the proposed Lyapunov function based controller for the VSC interface between the PV array and the power grid.

PI Controller model:

\[
e_p = (V_{dref} - V_d), \quad U_d = e_p \left( K_p + \frac{K_i}{1 + s T_p} \right) \quad (4.19)
\]

\[
e_q = Q_{qref} - Q_i, \quad U_q = e_q \left( K_q + \frac{K_{iq}}{1 + s T_q} \right) \quad (4.20)
\]
4.4 Lyapunov Function Based Sliding Mode Controller (LYPSMC) for VSC Interface

In designing a nonlinear controller for the VSC inverter, the dynamic model described in equations (4.15), (4.16), and (4.17) are used. The control quantities for the inverter are chosen to be the reactive power $Q$ and dc voltage $V_{dc}$ of the PV source. The PI controller has become the conventional structure for deciding the reference signal of the PWM switching control for many years. The conventional PI controllers, neither have disturbance rejection properties nor insensitive to system parameters variations, and application of non-linear loads.

For simplified analysis it is worthwhile to choose a local reference frame for the voltage source inverter that will result in making $V_{sd} = V_s$, and $V_{sq} = 0$, and this process simplifies the exact estimation of power flow to the converter. Thus the active and reactive power flow from the converter becomes $P_i = V_s i_{id}$, $Q_i = -V_s i_{iq}$, respectively. The following simplifications result by applying the above transformation to equations (4.15) to (4.17):

$$\frac{dP_i}{dt} = -\frac{R_i}{L_i} P_i - \omega_e Q_i + \frac{3}{2L_s} \left[ V_s U_d V_{dc} - V_s^2 \right]$$  \hspace{1cm} (4.21)

$$\frac{dQ_i}{dt} = -\frac{R_i}{L_q} Q_i + \omega_e P_i + \frac{3}{2L_s} \left[ -V_s U_q V_{dc} \right]$$  \hspace{1cm} (4.22)

where

$$U_d = \frac{m \cos \delta}{\sqrt{2}}, \quad U_q = \frac{m \sin \delta}{\sqrt{2}}$$  \hspace{1cm} (4.23)

To avoid some of the problems normally associated with PI controllers, this chapter has explored the use of Lyapunov based sliding mode control. Theoretically the robustness
of sliding-mode control can ensure accurate tracking performance even in the presence of model or parameter uncertainties. However, use of Lyapunov direct stability theorem ensures the possibility of adapting the control parameters during a sudden transient change or when the gains appear to be high when the state trajectory approaches the sliding surface. An important requirement of the sliding mode control design is to choose an appropriate sliding surface \( s(x) \) for the system state \( x \) so that state trajectories will be constrained to lie on it \( (s(x) = 0) \). However, the discontinuous nature of this control gives rise to chattering phenomenon and thus there is a need to convert the discontinuous control to a continuous one. For designing Lyapunov direct stability theorem based controller for the grid connected PV array, the following Lemma is followed:

For a continuous definite function \( V(t) \) to converge to the equilibrium point in finite time the equation given below is satisfied:

\[
\dot{V}(t) + \beta V(t) + \alpha V^\gamma(t) \leq 0, \forall t > t_0
\]  

(4.24)

This yields the time to convergence as

\[
t_\beta \leq t_0 + \frac{1}{\beta (1 + \gamma)} \ln \frac{\beta V_0^{1/\gamma}(t_0) + \alpha}{\alpha}
\]  

(4.25)

where \( \alpha > 0, \beta > 0, \) and \( 0 < \gamma < 1 \)

**Lyapunov function based Active and Reactive Power Controller**

To control the active and reactive power flow from the VSC interface of the PV array, two output states like the reactive power and the dc voltage are chosen. The reactive power regulates the ac voltage and active power control is achieved by regulating the dc voltage. To fulfill the control target objective the following equations are obtained at the equilibrium point from equations
\[
\begin{align*}
  u_d &= \frac{(3V_s^2 + 2R_i P_{\text{ref}} + 2\Omega_e L_i Q_{\text{ref}})}{3V_s V_{\text{dcref}}} \\
  u_q &= \frac{(-2R_i Q_{\text{ref}} + 2\Omega_e L_i P_{\text{ref}})}{3V_s V_{\text{dcref}}}
\end{align*}
\]  

(4.26)

\[
\frac{1}{C V_{\text{dc}}} (P_{\text{pv}} - P_{\text{ref}}) = 0 , \text{ and hence } P_{\text{ref}} = P_{\text{pv}}
\]

Here the active power management is to be done through the MPPT control and therefore the dc link voltage needs to be controlled. Another control variable is chosen as the reactive power. Thus by indirect Q-V control, the active power control is achieved. The next step is to design a sliding surface based on the reactive power and dc voltage errors based on the Lyapunov direct stability theorem. Therefore choosing the output states as \( y_1 = V_{\text{dc}} , y_2 = Q \), the sliding surfaces are obtained in the following way:

**DC Link voltage control**

The dc voltage error on the PV side is:

\[
e_{\text{dc}} = V_{\text{dc}} - V_{\text{dcref}}, \text{ and its derivative is}
\]

(4.27)

\[
\dot{e}_{\text{dc}} = \frac{1}{C V_{\text{dc}}} (P_{\text{pv}} - P) - V_{\text{dcref}}
\]  

(4.28)

Defining a PD type sliding surface for the dc voltage error, the following equation results:

\[
\sigma_{\text{dc}} = \dot{e}_{\text{dc}} + K_{dc} |e_{\text{dc}}|^{q/p} \text{sign}(\dot{e}_{\text{dc}}) , \text{ and } K_{dc} > 0
\]

(4.29)

\( p \) and \( q \) are positive odd integers, and \( q < p \).

Taking the derivative of the above

Substituting the values of the derivatives

\[
\dot{\sigma}_{\text{dc}} = a_1 - a_2 U_d
\]

(4.30)
where

\[ a_1 = \left(P_m - P_i\right)K_{dc} (q/p) e_{dc} |e_{dc}|^{q/p-1} \text{sign} \left( e_{dc} \right) + \frac{1}{CV_{dc}} \left( \frac{R}{L_i} P_i + \omega_2 Q_i + \frac{3}{2L_i} V_i^2 \right) \]

\[ a_2 = \frac{3V_s}{2L_i C} \]

**Reactive power control**

The reactive power error is given by

\[ e_Q = y_2 - y_{2\text{ref}} = Q_i - Q_{\text{ref}} \]  

(4.31)

Taking its derivative we get

\[ \dot{e}_Q = -\frac{R}{L_i} Q_i + \omega_2 P_i + \frac{U_p}{L_i} - \dot{Q}_{\text{ref}} \]  

(4.32)

A PI type sliding surface is used for the reactive power, which yields the following equation:

\[ \sigma_Q = \int_0^t \left( K_{1Q} e_Q + K_{2Q} e_Q^{q/p} \right) d\tau + e_Q, K_{1Q} > 0, K_{2Q} > 0 \]  

(4.33)

\[ \dot{\sigma}_Q = (K_{1Q} e_Q + K_{2Q} e_Q^{q/p}) - \frac{R}{L_i} Q_i + \omega_2 P_i + \frac{3}{2L_i} \left[ -V_s U_q V_{dc} \right] - \dot{Q}_{\text{ref}} = a_3 - a_4 U_q \]  

(4.34)

where

\[ a_3 = (K_{1Q} e_Q + K_{2Q} e_Q^{q/p}) - \frac{R}{L_i} Q_i + \omega_2 P_i - \dot{Q}_{\text{ref}}, a_4 = \frac{3}{2L_e} V_s V_{dc} \]
where the gains $K_{1q}$ and $K_{2q}$ control the convergence rate of the tracking dynamics.

Finally to obtain the control laws for the VSC interface, a positive definite Lyapunov function is chosen as

$$V = \frac{1}{2} \sigma_{dc}^2 + \frac{1}{2} \sigma_q^2$$

(4.35)

The derivative of $V$ is obtained as

$$\dot{V} = a_1 \sigma_{dc} - a_2 \sigma_{dc} U_d + a_3 \sigma_q - a_4 \sigma_q U_q$$

(4.36)

Hence from the Lyapunov’s second law, the stability of the VSC control is guaranteed for $\dot{V} < 0$ and to satisfy this condition, the control quantities are to be chosen as

$$U_d = \frac{a_1 + K_2 \sigma_{dc} + K_2 \sigma_{dc} |\sigma_{dc}| \text{sign}(\sigma_{dc})}{a_2}, \quad K_1 > 0, \quad K_2 > 0, \quad 0 < \lambda < 1$$

$$U_q = \frac{a_3 - K_3 \sigma_q + K_4 \sigma_q |\sigma_q| \text{sign}(\sigma_q)}{a_4}, \quad K_3 > 0, \quad K_4 > 0, \quad 0 < \lambda < 1$$

(4.37)

From equation (4.37), it is obvious that for large values of sliding surface gains $K_1, K_2, K_3$, and $K_4$, the reaching speed increases considerably. The $\text{sign}$ function used for the control inputs is a hard switched function, and thus a $\text{sat}$ function or $\text{tanh}$ function is used for the control inputs to make the controller chattering free and also of continuous switching type.

The $\text{sat}$ function is defined as

$$\text{sat}(\sigma_{dc}) = \text{sign}(\sigma_{dc}) \quad \text{if} \quad |\sigma_{dc}| \geq (1/\sigma_{dc}), \quad \text{and is equal to } \sigma_{dc} \text{ otherwise.}$$

Further for $\text{tanh}$ function the following value is used for real time implementation of the controller:
\[
\tanh(\sigma_{DC}) = \begin{cases} 
\text{sign}(\sigma_{DC}) & \text{if } |\sigma_{DC}| \geq 1 \\
\sigma_{DC}|\sigma_{DC}| + 2\sigma_{DC} & \text{if } |\sigma_{DC}| < 1 
\end{cases}
\] (4.38)

Similar expressions hold good for the sliding surface \(\sigma_q\).

Further to achieve an adaptive finite time control, the gains \(K_1, K_2, K_3, K_4\) are made adaptive in the following way:

\[
\begin{align*}
\dot{K}_1 &= K_{1n}\sigma_{DC}, & \dot{K}_2 &= K_{2n}\sigma_{DC}, \\
\dot{K}_3 &= K_{3n}\sigma_q, & \dot{K}_4 &= K_{4n}\sigma_q
\end{align*}
\] (4.39)

For sudden load changes at the PCC, the change in frequency is obtained from the active power-frequency characteristic as

\[
f - f_0 = -R_{droop}(P_t - P_p)
\] (4.40)

where \(f_0\) = nominal frequency.

From Lyapunov function considered in Eq. (4.35) the robustness and finite time convergence can be depicted as described below:

**Proof 1: Robustness of proposed LYPNSMC:**

By substituting the value of \(U_q\) from Eq. (4.37) into Eq. (4.30), it can be rewritten as:

\[
\dot{\sigma}_{DC} = -K_1\sigma_{DC} - K_2|\sigma_{DC}|^{\rho}\text{sign}(\sigma_{DC})
\] (4.41)

Similarly by substituting \(U_q\) in Eq. (4.34):

\[
\dot{\sigma}_q = -K_3\sigma_q - K_4|\sigma_q|^{\rho}\text{sign}(\sigma_q)
\] (4.42)
Now from above two solutions Eq. (4.35) can be redrafted as:

\[
\dot{V} = -K_1\sigma_{DC}^2 - K_2|\sigma_{DC}|^{q/p-1}\text{sign}(\sigma_{DC}) - K_3\sigma_q^2 - K_4|\sigma_q|^{q/p-1}\text{sign}(\sigma_q)
\]  

(4.43)

From Eq. (4.43), it can be shown that:

\[
\dot{V} = -K_1\sigma_{DC}^2 - K_2|\sigma_{DC}|^{q/p-1}\text{sign}(\sigma_{DC}) - K_3\sigma_q^2 - K_4|\sigma_q|^{q/p-1}\text{sign}(\sigma_q) \leq 0
\]  

(4.44)

As the Lyapunov function derivative is beyond limit zero, the tracking error will be convergence to the sliding surface, hence a robust controller.

**Proof 2: Finite time convergence of LYPSMC:**

From Eq. (4.29), when the tracking error is very close to the origin to be converged, \(\sigma_{DC} = 0\) ensures a finite time convergence expressed as:

\[
\frac{\dot{e}_{DC}}{K_{dc}|e_{DC}|^{q/p}\text{sign}(e_{DC})} = -1
\]  

(4.45)

By integrating with the convergence time limit:

\[
\int_{0}^{\Delta e_{DC}} \frac{1}{K_{dc}|e_{DC}|^{q/p}\text{sign}(e_{DC})} \Delta e_{DC} = \int_{0}^{\Delta_0} \dot{e} dt
\]  

(4.46)

Thus the tracking error will be convergence to sliding surface in finite time:

\[
\Delta_0 = \frac{1}{K_{dc}|e_{DC}|^{q/p}\text{sign}(e_{DC})}
\]  

(4.47)

**4.5 Computer Simulation Results**

Computer simulations are carried out using mathematical models of the PV array and the IGBT based VSC converter shown in Fig.4.3 to demonstrate the effectiveness of the
proposed Lyapunov theory based sliding mode controller in comparison to the conventional PI controller.

A 40 watt PV module is modeled on PV model: ELDORA40 and the datasheet values are listed in Table-4.1. The PV array of the proposed system is based on 20 parallel connected strings of the 40 watt module where each string is containing 14 modules in series. The following case studies are carried out:

**Case-1 (Change in reference parameter):**

Tracking capability of both the controllers is examined by applying step commands to $P_{ref}$ from 0.7022 to 0.8658 p.u., $Q_{ref}$ from 0.0744 to 0.4 p.u., and $V_{dc ref}$ from 1.6695 to 2.0747p.u. at $t=0.1s$, respectively. The PI controller gains are obtained using ITAE criterion as

PI: $K_p=75, K_q=1, K_{ip}=3600; K_{iq}=4820$. The *gain margin* and *% overshoot* values of SISO system created by PV-VSC grid and PI control, are used to determine the $K_p$ and $K_i$ gain values for PI control.

The Lyapunov sliding mode controller gains are:

LYPSM: $K_{iq}=150; K_{2q}=50; K_{dc}=1.0; K_1=10.4; K_2=5.4,$

$K_3=10, K_4=6.3, \frac{q}{p}=0.8,$

$T_p=0.1sec, T_q=0.1sec$. The proposed control values are determined by Lyapunov finite time theory. The stability proof Eqs (4.44) and (4.47) are considered for those gain parameter tuning.

From the transient response shown in Fig.4.4 it is clear that the settling time to the active and reactive power commands are 0.6 and 0.2 sec, respectively. For the PI controller the
corresponding settling times are 1.0 sec. for both the active and reactive power commands. Also it is observed that the PI controller exhibits significant amount of high frequency oscillations before settling to the final value for the PCC voltage. The frequency of the PCC voltage shows an initial rise and then settle down to its original value in 0.8s for the LYPSM controller in comparison to PI controller that exhibits severe oscillations.

Table-4.1: PV module parameters from model: ELDORA 40

| Number of parallel and series cells, \( n_p \) | 36 |
| Cell’s open circuit voltage, \( V_{oc} \) | 21.90 V |
| Cell’s \( V_{mpp} \) at STC | 17.40 V |
| Cell’s short circuit current, \( I_{sc} \) | 2.3A |
| Cell reverse saturation current, \( I_{rs} \) | 1.2e-7A |
| Charge of an electron, \( q \) | \( 1.602 \times 10^{-19} \)C |
| Boltzmann’s constant, \( k \) | \( 1.38 \times 10^{-23} \)J/K |
| Ideality factor, \( A \) | 1.92 |
| Cell’s reference temperature, \( T_{ref} \) | 300[K] |
| coefficient of cell, \( K_f \) | 0.0017 |

Other system parameters are: \( R_g=15mΩ, L_s=0.637mΩ, R_y=10mΩ, L_y=0.5mΩ, C_{dc} =0.5mF \)

\( P_{base}=10kVA, V_{base}=115V(L-L), V_{dc(base)}=115V, R_{d\mu \rho e p} =0.05 \)
Case-2 (Change in insolation): At t=0.1s, there is a step increase in insolation level from the initial level of 500 W/m² (50%) to 900W/m² (90%) during a period of 0.1s to 0.4s. From 0.4s to 0.7s the level of insolation is reduced again to 50%. At 0.7s the insolation level is increased to 80% and is maintained at that level. Fig.4.5 shows the transient response of the PV array showing clearly the effectiveness of the LYPSPM controller over the conventional PI controller.
Case-3 (Change in load): Fig. 4.6 shows that, the controllers are able to track the open circuit photovoltaic voltage of 282.6246 V (2.4576 p.u.) when the load is disconnected from the PV array, such that the power generated by PV array is 0 W. From the figure it is clear that the LYSMC outperforms the PI controller in reducing the oscillations faster.
Fig. 4.5. Tracking of maximum power for different insolation levels
Fig. 4.6. Tracking of open circuit dc-link voltage for an isolated PV array
Case-4 (Fault in utility grid): A 3-phase fault is initiated at time $t = 0.1$ sec and cleared at 0.2 sec. Prior to the fault, the values of reference active and reactive powers are: $P_{\text{ref}} = 0.7022$ p.u., and $Q_{\text{ref}} = 0.0744$ p.u. Fig. 4.7 shows that the controllers are able to come back to the pre-fault after the fault is cleared. As expected the LYPSM controller reduces the oscillations much faster than the corresponding PI controller.
Case-5 (Parametric change): Between $t=0.1\, \text{s}$ to $t=0.2\, \text{s}$, the converter resistance $R_i$ and inductance $L_i$ are changed to thrice and twice of their steady state values, respectively. Fig.4.8. shows that the controllers are able to restore the steady state values. The PI controller exhibits severe oscillations in comparison to the proposed LYPSM controller.

Fig.4.7. Controller performance under grid fault
Fig. 4.8. Controller performance to change in converters parameters
Case-6 (Operation during islanding): The system is at steady state feeding the required power to the load before islanding occurs. At $t=0.4s$, the grid is disconnected from the substation and load is made to operate at 120% of active power of PV system shown in Fig.4.9.
From the figures it is observed that the frequency is slightly increased from 59.97 to 60 Hz, and active, reactive power, voltage at the PCC, etc. exhibit reductions during islanding.
Performance evaluation between two controls:

The proposed control strategy is more efficient and robust during uncertainty and fault conditions, as clarified in various case studies mentioned above. A statistical review between proposed LYPSM control and conventional PI control is further given to support the superiority of non-linear LYPSM control. The data are extracted on the basis of active and reactive power parameters at PCC and presented in Table -4.2.

Table 4.2: Comparative study between conventional and proposed control

<table>
<thead>
<tr>
<th>Case studied</th>
<th>PI control error mitigation</th>
<th>Proposed control error mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-1 (Change in reference parameter):</td>
<td>More than 50 cycles</td>
<td>10-30 cycles</td>
</tr>
<tr>
<td>Case-2 (Change in insolation):</td>
<td>30-45 cycles</td>
<td>8-20 cycles</td>
</tr>
<tr>
<td>Case-3 (Change in load):</td>
<td>30 cycles</td>
<td>8-10 cycles</td>
</tr>
<tr>
<td>Case-4 (Fault in utility grid):</td>
<td>44 cycles</td>
<td>8 cycles</td>
</tr>
<tr>
<td>Case-5 (Parametric change):</td>
<td>38 cycles</td>
<td>2-6 cycles</td>
</tr>
</tbody>
</table>

The bar graph representation of above data is clearly justifying the admissibility of the LYPSM control over conventional PI control:

![Performance of two control](image)

Fig. 4.10. Graphical representation of comparative study between two controls
Grid interactive PV system with LYPSM control- MATLAB/SIMULINK validation:

To validate the efficacy of the proposed control, a 100 kW, 260 volt model of grid connected photovoltaic system is simulated using MATLAB/SIMULINK software and the control block diagram is shown in Fig.4.11. Some of the important tests are given in the following case studies:

A.Infinite Bus Fault

A three phase fault from time = 1 to 1.2 sec duration has been initiated near the grid and the transient response of various system states like the voltage at the PCC, phase current, active, and reactive power, dc link voltage on the PV side are shown in Fig.4.12. From the observed response it is quite clear that the proposed LYPSM controller produces better damping and fewer oscillations of the various system states in comparison to the PI controller that exhibits greater overshoot, sluggish response, and higher settling time.
Fig. 4.11: (a) Simulation diagram of proposed system, (b) inside VSC control: Block diagram for generating Q-V control laws for the PV array VSC system.
Plot PV voltage vs time

Plot Active Power at PCC vs time

Plot Reactive Power at PCC vs time
B. Change in insolation

The second case which has been studied for validation of proposed controller performance is change in solar insolation (W/m²). The test scenario is insolation changes from 1000 W/m² to 800 W/m² and temperature changes from 25 °C to 35 °C at time=1 sec. the performance behavior is as below:
Plot PV voltage vs time

- LYPSM
- P.I control

Plot Active Power at PCC vs time

- LYPSM
- P.I control

Plot Reactive Power at PCC vs time

- LYPSM
- P.I control
Figure 4.13: comparative study of (a) PV side voltage of VSC, (b) active power at PCC, (c) reactive power at PCC, (d) one phase voltage at PCC, (e) one phase current at PCC.

The various case studies verified the proposed LYPSM is robust control during dynamic changes and providing stable, reliable grid operation compared with conventional control.
4.6 CONCLUSION

A new nonlinear control strategy for a 3-phase grid connected PV generation system is proposed in the chapter. The VSC converter interface between the PV array and the grid is modeled in a stationary phase frame using active and reactive powers, and dc voltage as dynamic variables. A robust sliding mode control strategy using Lyapunov’s direct stability theorem has been developed in the chapter using the reactive power and the dc link voltage errors. The proposed Lyapunov-function-based finite time nonlinear control is easier to implement while providing significant improvement in performance in comparison to the conventional PI controller. Further the instantaneous active and reactive power waveforms are not influenced by the PLL dynamics. The simulation results obtained from MATLAB/SIMULINK PV system model show clearly that the LYPSCM controller produces less harmonics in comparison to the PI controller.