Abstract—This paper proposes a novel robust & adaptive sliding mode (SM) control for a cascaded two-level inverter (CTLI)-based grid connected photovoltaic (PV) system. The modelling and design of the control scheme for the CTLI-based grid connected PV system is developed to supply active power and reactive power with variable solar irradiance. A vector controller is developed keeping the maximum power delivery of the PV in consideration. Two different switching schemes have been considered to design SM controllers and studied under similar operating situations. Instead of the referred space vector PWM technique, a simple PWM modulation technique is used for the operation of the proposed SM controller. The performance of the SM controller is improved by using an adaptive hysteresis-band (HB) calculation. The controller performance is found to be satisfactory for both the schemes at considered load and solar irradiance level variations in simulation environment. The laboratory prototype, operated with the proposed controller is found to be capable of implementing the control algorithm successfully in the considered situation.

Index Terms—Photovoltaic (PV) system, multilevel inverter, Vector control, sliding mode control (SMC), distribution static compensator (Distribution-STATCOM)
In this work, the PV modules are designed to produce a dc voltage of 48 V at a normal Indian solar irradiance. This voltage is then converted to an ac voltage of 400 V (line to line) using a grid-tied inverter. The complete multidimensional array model equation is developed using a vector control scheme.

The characteristic equation of PV cells is given by (1):

\[ V_{oc} = q \left( \frac{V_{oc}}{N_{ph}} \right) + IR + \frac{V_{oc}}{R_{sh}} \]

To improve the performance of SMC, the present work proposes a novel control scheme. This scheme ensures the maximum power delivery of the system at a normal Indian solar irradiance. The parameter values are determined from the equation (2):

\[ I = I_{ph} - I_s \left( \frac{1}{nKT} \right) - \frac{V}{R_{sh}} \]

A novel SM control scheme is proposed so that the output currents of the inverter are controlled to match the current reference. This control is highly suitable for applications in power electronics, e.g., electrical drives, high-voltage and high-power converters, and their wide utilization in industrial applications, etc.

The SMC control suffers from chattering problem, which leads to variable and high frequency switching in the parallel inverters [5], [20] as VSIs, dc-dc converters [15], [18] with a simple PWM technique instead of referring to a hysteresis band in the hysteresis modulator of the SM [19]. However, one of the robust and dynamic control techniques is the sliding mode control (SMC). This control is based on Lyapunov stability theory. In general, SMC is characterized by a switching control law, which ensures the convergence of the system to the desired equilibrium point. The sliding surface is chosen as a function of the error and its derivative. The typical sliding surface is as follows:

\[ S = V_k - V \]

where \( V_k \) is the voltage reference and \( V \) is the actual voltage. The control input is designed to make the error converge to zero along the sliding surface. The control input is given by:

\[ u = \text{sign}(S) \cdot k \]

where \( k \) is a gain. The gain \( k \) is chosen such that the system is stable and the error converges to zero. The sliding mode control is characterized by a chattering problem, which can be reduced by using a smooth control law. The smooth control law is designed to approximate the discontinuous control input.

The photovoltaic systems are connected to the grid tied inverter, and the complete power scheme is shown in Fig. 1. The parameter values are determined from the equation (2):

\[ I = I_{ph} - I_s \left( \frac{1}{nKT} \right) - \frac{V}{R_{sh}} \]

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is defined by the following control law:

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
= \begin{bmatrix}
-\sqrt{3} & 0 & 0 \\
0 & \sqrt{3} & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\gamma_a \\
\gamma_b \\
\gamma_c
\end{bmatrix}
V_{dc}
\]

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
= \begin{bmatrix}
-\sqrt{3} & 0 & 0 \\
0 & \sqrt{3} & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\gamma_a \\
\gamma_b \\
\gamma_c
\end{bmatrix}
V_{dc}
\]

The d-q axis of the used vector can be

\[
\begin{bmatrix}
\gamma_a \\
\gamma_b \\
\gamma_c
\end{bmatrix}
= \begin{bmatrix}
\gamma_1 \\
\gamma_2 \\
\gamma_3
\end{bmatrix}
V_{dc}
\]

Applying KVL for ‘a’, ‘b’ and ‘c’ phases:

\[
\begin{align*}
\bar{n} (a) - e_{\gamma} &= n_a i_a + L_a \frac{di_a}{dt} + V_a \\
\bar{n} (b) - e_{\gamma} &= n_b i_b + L_b \frac{di_b}{dt} + V_b \\
\bar{n} (c) - e_{\gamma} &= n_c i_c + L_c \frac{di_c}{dt} + V_c
\end{align*}
\]

where, \( R, L_a, L_b, \) and \( L_c \) are considered to be equal to 1: n.

Fig. 5. Vector diagram of the voltage

\[
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix}
= \begin{bmatrix}
\gamma_1 \\
\gamma_2 \\
\gamma_3
\end{bmatrix}
V_{dc}
\]

Here, \( s_y \) is the grid voltage, \( e_{\gamma} \), \( e_{\gamma} \), \( e_{\gamma} \) and \( e_{\gamma} \) are the primary of the

\[
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix}
= \begin{bmatrix}
\gamma_1 \\
\gamma_2 \\
\gamma_3
\end{bmatrix}
V_{dc}
\]

A. CTLI model

\[
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix}
= \begin{bmatrix}
\gamma_1 \\
\gamma_2 \\
\gamma_3
\end{bmatrix}
V_{dc}
\]

B. Vector control

\[
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix}
= \begin{bmatrix}
\gamma_1 \\
\gamma_2 \\
\gamma_3
\end{bmatrix}
V_{dc}
\]

Accordingly, the controllers are designed to maintain the total

\[
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix}
= \begin{bmatrix}
\gamma_1 \\
\gamma_2 \\
\gamma_3
\end{bmatrix}
V_{dc}
\]

Thus, the controllers are designed to maintain the total

\[
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix}
= \begin{bmatrix}
\gamma_1 \\
\gamma_2 \\
\gamma_3
\end{bmatrix}
V_{dc}
\]
A variable structure control (VSC) is used. The switching surface is described by

\[
\begin{align*}
\dot{S}_p &= \mathbf{i}_d - S_p \\
\dot{S}_m &= \mathbf{i}_q - S_m \\
\dot{S}_b &= \mathbf{V}_d - S_b \\
\end{align*}
\]

where \(S_p, S_m, S_b\) are the switching variables, \(\mathbf{i}_d, \mathbf{i}_q\) are the \(d, q\) axes components of the cascaded inverter current, and \(\mathbf{V}_d, \mathbf{V}_q\) are the \(d, q\) axes components of the cascaded inverter voltage. The total output current is \(\mathbf{i}_d + \mathbf{i}_q\), and the total output voltage is \(\mathbf{V}_d + \mathbf{V}_q\).

The dynamic behavior of the rectifier can be represented by

\[
\begin{align*}
\dot{i}_d &= -\frac{R}{L}i_d + \frac{1}{L}v_d - \frac{1}{L}v_{dc} \\
\dot{i}_q &= -\frac{R}{L}i_q - \frac{1}{L}v_q + \frac{1}{L}v_{dc} \\
\dot{v}_d &= \frac{1}{C}v_{dc} - \frac{1}{C}v_d \\
\dot{v}_q &= \frac{1}{C}v_{dc} - \frac{1}{C}v_q \\
\end{align*}
\]

where \(R, L, C\) are the resistance, inductance, and capacitance, respectively, \(v_d, v_q\) are the \(d, q\) axes components of the voltage across the inductor, \(v_{dc}\) is the dc-link voltage, and \(v_{dc}\) is the dc-link voltage. The total output current is \(\mathbf{i}_d + \mathbf{i}_q\), and the total output voltage is \(\mathbf{V}_d + \mathbf{V}_q\).

C. Sliding mode control (SMC)

The sliding mode control (SMC) is implemented using either sliding mode PWM or hysteresis modulation technique in the two switching schemes, which are discussed as follows.

Two-Level Switching: Scheme-I

The voltage controls are usually realized with conventional one. This SMC is designed considering first a controller constant \([15]\). (a) Constant ramp or timing functions do not require additional computation or auxiliary circuitries. (b) Controller constant \([15]\). (c) Constant controlled through varying the ramp/timing function. (c) Variable controlled through varying the ramp/timing function. (c) Constant controlled through varying the ramp/timing function.

Forced Switching: Scheme-II

This work, presents the main steps to design the SMC, from one continuous structure to another, according to the discontinuous control law that switches at a high frequency to counteract the switching frequency variation. (c) Constant controlled through varying the ramp/timing function. (c) Variable controlled through varying the ramp/timing function.
Adaptive HB calculation for SMC

\[ \frac{di_1}{dt} = V_{dc} \]
\[ \frac{di_2}{dt} = -V_{dc} \]
\[ \frac{di_3}{dt} + L \frac{di_4}{dt} = \infty \]
\[ \frac{di_5}{dt} = \infty \]
\[ \frac{di_6}{dt} = \infty \]

From the geometry of Fig. 9, it can be found

\[ V_{dc} = \frac{mLV_{HB} Lf V}{f_{sw}} \]

The control strategy must guarantee that the system

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

Fig. 9 which, in turn, yields the voltage-current relationship as

\[ V_{dc} = \frac{mLV_{HB} Lf V}{f_{sw}} \]

The calculation of hysteresis band is accomplished by

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

Now, using (30), (34) and (35) it can be found that

\[ \frac{di_3}{dt} - t \frac{di_4}{dt} = \infty \]
\[ \frac{di_5}{dt} = \infty \]

Further, subtracting (32) from (31), one obtains

\[ \frac{di_3}{dt} - t \frac{di_4}{dt} = \infty \]
\[ \frac{di_5}{dt} = \infty \]

Let

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

Therefore, it is essential to calculate the optimal magnitude of

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

sliding surfaces suitable to control variables

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

The following sliding surfaces should be zero after reaching

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

any initial condition. In order to achieve this strategy, the

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

trajectory moves towards and stays on the sliding surface from

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

the carrier.

Accordingly the switching law is selected as

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

Therefore, it is essential to calculate the optimal magnitude of

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\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

sliding surfaces suitable to control variables

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

The inverter may enter into complex switching states below

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

the carrier.

Accordingly the switching law is selected as

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

Therefore, it is essential to calculate the optimal magnitude of

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

sliding surfaces suitable to control variables

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]

The control strategy must guarantee that the system

\[ s_i e_a(t) \equiv i_2 - i_3 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ s_a e_a(t) \equiv i_4 - i_5 = \infty \]
\[ HB = \frac{Y_{dc}}{L_{f_{rs,ideal}}} \]

\[ P = \frac{\dot{d}V_d}{2} \]

A. Active power variation for two switching schemes

<table>
<thead>
<tr>
<th>S. No.</th>
<th>PARAMETER</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( e_d )</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>( e_q )</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>( e_r )</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>( i_d )</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>( V_d )</td>
<td></td>
</tr>
</tbody>
</table>

\[ \Delta V = 20 \text{V} \]

\[ \Delta t = 0.5 \text{s} \]

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Solar deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-20</td>
</tr>
<tr>
<td>0.5</td>
<td>-10</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1.5</td>
<td>20</td>
</tr>
</tbody>
</table>

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C. Operation as Distribution STATCOM

\[ Q = - \frac{3}{2} (i_q V_d) \]

B. Active power variation for forced switching schemes

The solar irradiance is varied in the same manner as it was considered schemes is then tested in the absence of solar grid only. The total dc-link voltage suffers no disturbance because of this load change and maximum power delivery from the solar panels is found unaltered.

\[ \text{Fundamental (50Hz) = 38.61, THD= 1.79\%} \]

\[ \text{Current (A)} \]

\[ \text{Time (s)} \]

\[ \text{Voltage (V)} \]

\[ \text{Time (s)} \]

\[ \text{Current (A)} \]

\[ \text{Time (s)} \]

\[ \text{Voltage (V)} \]

\[ \text{Time (s)} \]

\[ \text{Current (A)} \]

\[ \text{Time (s)} \]

\[ \text{Voltage (V)} \]

\[ \text{Time (s)} \]
D. Experimental Results

The simulation and experimental results are presented in Fig. 17. The equipments, used to prepare the experimental scheme, using dSPACE1104 with two inverters, are mentioned in Table II. The experimental results are exactly following the theoretical counterparts in Fig. 18. The simulation results are presented in Fig. 19. Experimental Results at steady state operation: (a) total dc voltage of inverter(s), and (b) transformer output current for two phases are shown in Fig. 19 (b).

<table>
<thead>
<tr>
<th>S. No.</th>
<th>PARAMETER</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Solar module (two no. for two inverters)</td>
<td>30F+MDB6CI400/220</td>
</tr>
<tr>
<td>2.</td>
<td>Inverter (two numbers)</td>
<td>IGBT (SKM75GB123D)</td>
</tr>
<tr>
<td>3.</td>
<td>Transformer</td>
<td>1650 μF</td>
</tr>
<tr>
<td>4.</td>
<td>Load</td>
<td>R, L, C</td>
</tr>
</tbody>
</table>
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results closely match with the simulation results in the scheme in real time through dSPACE 1104. The experimental

References

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