Abstract

Renewable sources of energy are gaining importance with each passing day. In order to increase the penetration of renewable sources of energy, they must have some reserve capacity for stable operation and higher reliability. Generally PV systems are equipped with sufficient battery backup when interfaced with any load network. However, installation and maintenance of batteries for high power systems becomes difficult from economic perspective. On the other hand, grid connected PV systems are relatively more stable and robust. In this paper, a sliding mode based power balancing control strategy for grid connected solar PV systems is proposed. Some of the advantages of sliding mode control are disturbance rejection, insensitivity to parameter variation and simple implementation. The proposed control strategy can provide power balancing and reserve capacity without use of expensive energy storage devices like batteries. Simulations are carried out under varying load demand as well as changing weather conditions to demonstrate the applicability and effectiveness of the proposed sliding mode control strategy.

Keywords: BEES, Maximum Power Point Tracking, Sliding Mode Control, Voltage Source Converter

1. Introduction

With growing energy demand and climate change concerns, it is increasingly becoming clearer that dependency on conventional energy sources, particularly fossil fuel based sources must be reduced gradually. Alternative/renewable energy sources are going to play a vital role in reducing the energy deficit for re-emerging nations such as India. Installed capacity of various renewable sources of energy such as, solar, wind, tidal etc. is increasing rapidly and steadily. Integrating these systems with conventional grid has posed many challenges, such as, synchronization, effect on harmonic interactions, effect on power quality, aspects related to control and system stability, coordination over large spatial distances, etc. Solar energy is a preferred renewable energy source as it can be used in remote, rural areas as well as urban areas that receive sufficient sunlight for most part of the year. Both standalone and grid connected Solar Photovoltaic Systems (SPV) are being used. One major disadvantage of standalone system is low reliability, which can be often compensated through expensive batteries. However, grid integration of renewable SPV systems offers a viable option with high reliability and low cost. As stated earlier, integration of SPV systems with the grid is increasing and has posed new challenges.

Most of the present SPV energy systems use a Maximum Power Point Tracking (MPPT) algorithm to extract maximum available power from the PV modules. A large number of MPPT algorithms have by means of conventional power converters.

Many algorithms been proposed in the literature, e.g. perturb & observe, incremental conductance, fractional open circuit voltage (VOC), fuzzy logic based algorithm etc. All these algorithms try to extract maximum power all the time. However for a distributed generation system, there may be situations when SPV systems are not supposed to generate maximum power. With distributed generation systems, it is important that each generation unit has some reserve power capacity. Such reserve power capacity ensures reliable and stable power system in presence of sudden spikes in power demand. Further, extracting maximum power all the time makes the system vulnerable to sudden climatic changes and can cause
problems such as DC-link voltage collapse or sudden reduction in power output. Limited power point tracking is thus very important for SPV systems. Limited Power Point Tracking (LTTP) algorithm has also been used for frequency regulation of a micro-grid using solar power.

Currently, renewable energy systems are usually equipped with batteries for power balancing. Many Battery Energy Storage Systems (BESS) are also coming-up in order to meet sudden load variations. BESS achieves power balancing, DC-link voltage stabilization and reserve power during insufficient power conditions. Renewable energy systems that are interfaced with the help of batteries to a distribution network have two major disadvantages: 1. It makes the entire system costly and 2. They also require continuous maintenance/replacement of batteries as they have short-life as compared to other system components. Therefore, in this paper grid connect SPV systems are considered.

In this paper, a control strategy for power balancing for grid connected SPV systems is proposed to eliminate the use of batteries or any other expensive energy storage devices. A sliding mode controller is used to control power generated from PV array in a grid connected SPV system. The proposed sliding mode controller provides robustness to parameter changes, quick disturbance rejection and tight control over the PV power. There are two sliding modes of operation: sufficient power condition and insufficient power condition. For a given insolation level, if the power requirement is lower than the PV capacity then the system operates under limited power point tracking i.e. the amount of power generated will be just enough to meet the load demand. On the other hand, if the load power requirement is higher than what SPV system can generate then the system works under maximum power point tracking. This control provides reserve capacity to SPV system and can be used in situations where there are constraints over the power supplied by the grid, e.g. rating of distribution transformer may determine how much power can be drawn from the grid. The main advantage of having reserve capacity to the system is that the system can deal with sudden changes in power demand and climate conditions. Thus having reserve capacity facilitate stable operation of the system. The proposed control algorithm can also be used under islanded condition, albeit constrained by the maximum generation capability of the SPV system. Similarly, the proposed control strategy can also be used for reactive power compensation as it has been shown that the VSI (CSI) can be used to control active and reactive power flow through inverter. Simulations were carried out to demonstrate effectiveness of the proposed control strategy under varying load demand as well as climate conditions.

The remainder of the paper is organized as follows: the system under consideration is described in section II, followed by system model description in section III. The proposed sliding mode control law is derived in section IV. Section V describes the simulation results and section VI ends with some concluding remarks.

2. System Description

In this paper, a Photovoltaic System with peak power capacity of 50 kW is interfaced with three-phase three-wire grid with a shunt connected local load network. A two-stage topology is implemented for interfacing PV system to the distribution network as shown in the Figure 1. The first stage consists of a non-isolated DC-DC buck converter. The main objective of power balancing is achieved through this buck converter. The buck converter operates in two operating regimes: 1. When PV system output power is sufficient to supply the total load demand and 2. When PV system output power is insufficient to supply the load demand and the SPV system is at Maximum Power Point (MPP). The control technique used for the converter to operate it in both the regimes is sliding mode technique. A three-leg two-level Voltage Source Inverter (VSI) is used for transferring the power from PV panels to the Point of Common Coupling (PCC) and to meet the reactive power requirement of the system if any. Current Source Inverters (CSI) can also be used with the proposed control technique and it will not affect the system as both the proposed sliding mode control of buck converter and the current control of inverter are independent of each other. Three inductors are used to interface the inverter with the grid. A shunt RC-filter is used as a ripple filter to remove high frequency ripple, which are caused due to high frequency switching of the inverter, from the PCC voltage. The SPV system and the PV panel parameters are given in Table 1 and Table 2.

<table>
<thead>
<tr>
<th>Table 1. System parameters</th>
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<tr>
<td><strong>C</strong> (output capacitance of buck converter)</td>
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<tr>
<td><strong>L</strong> (inductance of buck converter)</td>
</tr>
<tr>
<td><strong>f_s</strong> (switching frequency of buck converter)</td>
</tr>
<tr>
<td><strong>L_{in}</strong> (interfacing inductance)</td>
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<tr>
<td><strong>V_{ll}</strong> (line to line grid voltage)</td>
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\[ I_{pv} = N_p I_{ph} - N_p I_{st} \left( \frac{qV_{pv}}{kTAN} - 1 \right) \]  

where \( N_s, N_p \) are the number of PV modules connected in series and parallel, respectively. \( I_{ph} \) is output current of the PV system and \( V_{pv} \) is the output voltage of the PV system. The SPV system is interfaced with a buck converter for power balancing. The buck converter modeling is explained in the next subsection.

### 3.2 Buck Converter Modeling

A nonlinear state space model of buck converter is used here.

\[ \dot{V}_{pv} = \frac{I_{pv}}{C} - \frac{I_0}{C} u \]
\[ \dot{i}_0 = -\frac{V_{pv}}{L} u \]

where the states \( I_0, V_{pv} \) are the output current and voltage of the buck converter, respectively. The input \( u \) is 0 when the switch is OFF and 1 when the switch is ON. The non linear state space model is given as,

\[ \dot{x} = f(x) + g(x)u \]

where, \( x = \begin{bmatrix} V_{pv} & I_s \end{bmatrix}^T \), \( f(x) = \begin{bmatrix} \frac{I_{pv}}{C} - \frac{V_{pv}}{L} \end{bmatrix}^T \) and \( g(x) = \begin{bmatrix} -\frac{I_0}{C} & \frac{V_{pv}}{L} \end{bmatrix}^T \)

### 4. Control Structure

The overall control structure of the proposed power balancing control strategy is shown in Figure 2. The entire
control system is divided into three parts: 1. Sliding mode PV power control, 2. DC-link voltage control and 3. Inverter current control. In the following subsections, each of these control systems is explained in detail.

4.1 Sliding Mode Controller

The sliding mode control is a technique that maintains the system trajectory along a particular surface, which is commonly called a sliding regime or a sliding surface. A smoothing function \((s(x))\), which reflects the dynamics of the sliding mode regime, is defined. A general control law for sliding mode control \(^{16}\) can be represented by

\[
  u = \begin{cases} 
  u^+ & \forall s(x) < 0 \\
  u^- & \forall s(x) > 0 
  \end{cases} 
\] (6)

where \(u^+\) and \(u^-\) are the control inputs to be applied whenever \(s(x)\) is nonzero.

For the proposed sliding mode power-balancing controller, a smoothing function based on \(V_{pv}\) and \(I_{pv}\) is chosen. It is assumed here that the SPV system power output \((P_{ref})\) is given and the sliding mode controller must maintain \(P_{ref}\). For a distributed generation scenario, the SPV system may be getting the power generation set-point \((P_{set})\) either from a supervisory controller, or \(P_{ref}\) may be decided based on a combination of load forecast and generation forecast.

Depending upon the instantaneous value of \(P_{ref}\) and maximum power generation capacity \((P_{max})\) (which is dependent on the insulation level) of the SPV system, the buck converter is operated in one of the two modes: 1. Power sufficient mode (when \(P_{max} \geq P_{ref}\)) and 2. Power insufficient mode (when \(P_{max} < P_{ref}\)). A variable structure control \(^{16,17}\) is used for operating the buck converter in both the modes i.e. power sufficient mode and power insufficient mode. Thus during power sufficient mode, the SPV system must operate in LPPT mode and during power insufficient mode, the SPV system operate in MPPT mode. The propose control strategy provides such flexibility to operate in any of the two modes, depending on the load, climate conditions and status of the distributed generation system. Two different smoothing functions are chosen for the two modes of operation, as explained here.

In power sufficient mode, the smoothing function \(s_1(x)\) is taken to be

\[
  s_1(x) = P_{pv} - P_{ref} = 0 
\] (7)

where, \(P_{pv}\) is the instantaneous power output of the SPV System, given by \(V_{pv}I_{pv}\). To achieve the sliding mode regime the transversality condition has to be satisfied \(^{16}\).

\[
  L_2 s_1 = \frac{\partial s_1}{\partial x} g(x) = -J I_{pv} \frac{\partial I_{pv}}{\partial V_{pv}} + \frac{I_{pv}}{V_{pv}} \geq \frac{2 I_0}{CV_{pv}} \geq 0 
\] (8)

For the above transversality condition, the control law \((u)\) for power sufficient mode must be given as,

\[
  u = \begin{cases} 
  0 & \forall s_1(x) \geq 0 \\
  1 & \forall s_1(x) < 0 
  \end{cases} 
\] (9)

When the buck converter is operating in power insufficient mode, another smoothing function \(s_2(x)\) is taken.

\[
  s_2(x) = \left( \frac{\partial I_{pv}}{\partial V_{pv}} + \frac{I_{pv}}{V_{pv}} \right) = 0 
\] (10)

To achieve the sliding mode regime for \(s_2(x)\), the following transversality condition has to be satisfied.

\[
  L_2 s_2 = \frac{\partial s_2}{\partial x} g(x) = - \frac{I_0}{CV_{pv}} \left( \frac{\partial I_{pv}}{\partial V_{pv}} + \frac{I_{pv}}{V_{pv}} \right) \geq \frac{2 I_0}{CV_{pv}} \geq 0 
\] (11)
For the above transversality condition the control law \((u)\) for power insufficient mode must be given as

\[
u = \begin{cases} 
0 & \forall s_2(x) \geq 0 \\
1 & \forall s_2(x) < 0 
\end{cases}
\]  
(12)

When both the smoothing functions are combined, the complete sliding mode control algorithm can be obtained as,

\[
u = \begin{cases} 
0 & \forall s_1(x) \geq 0 \& P_{max} \geq P_{ref} \\
1 & \forall s_1(x) < 0 \& P_{max} \geq P_{ref} \\
0 & \forall s_2(x) \geq 0 \& P_{max} < P_{ref} \\
1 & \forall s_2(x) < 0 \& P_{max} < P_{ref} 
\end{cases}
\]  
(13)

The output of the sliding mode controller \((u)\) will drive the buck converter as shown in Figure 3. The actual power output of the SPV system \((P_{act})\) is given by \(P_{act} = V_{pv}I_{pv}\). The second component of the control strategy, DC-link voltage controller is explained in the next subsection.

### 4.2 DC-link Voltage Controller

For satisfactory operation of the inverter, the DC-link voltage should be maintained at a suitable voltage level, which is given by the following expression\(^{18-20}\):

\[V_{dc}^* = \frac{2\sqrt{2}V_{in}}{\sqrt{3m}}\]  
(14)

where, \(V_{in}\) is the line to line voltage of the grid, and \(m\) is the modulation index. For the system parameters considered in this paper, the DC-link voltage should be maintained at 700V. In order to maintain this voltage level, a PI-controller is used (Figure 3). Reference DC-link voltage \((V_{dc}^*)\) is compared with actual DC-link voltage \((V_{dc})\) and the error signal is given to the PI controller. The output of the PI controller determines current reference \((i_d^*\) and \(i_q^*)\) for the VSI.

### 4.3 Inverter Current Controller

Hysteresis current control technique is used to control the power flow through the inverter. The \(P_{act}\) coming from the SPV system is used to calculate the dq-frame current references \((i_d^*\) and \(i_q^*)\). The output from the PI controller of DC-link voltage controller is added to the \(I_{act}\) obtained from the \(P_{act}\). The final \(i_d^*\) and \(i_q^*\) (obtained from), which are in dq0 reference frame (synchronous reference frame) are converted into abc frame (stationary reference frame) using a PLL.

\[I_d = I_{dref} + K_P \Delta V_{dc} + K_I \int \Delta V_{dc} dt\]  
(15)

The PLL synchronizes the inverter voltage with the grid voltage. The reference values thus obtained in stationary reference frame are subtracted from the instantaneous values of individual phase currents \(i_a, i_b, i_c\) and then given to the hysteresis controllers operating with a band limit of (-0.2 A & 0.2 A). The output of this hysteresis controller is then given to relays, which will finally give the switching signals for inverter circuit. The controller parameters are given in Table 3.

### 5. Simulation and Results

To demonstrate effectiveness and applicability of the proposed control strategy, simulations were carried out for various modes of operation. The simulation cases considered here are chosen to demonstrate the usefulness of the control algorithm under varying load demand as well as varying climate conditions.

#### 5.1 Case-1: Sudden Change in Load Demand

First simulations were carried out for variable load demand during power sufficient mode. Initially the SPV system was operating under steady state condition with load demand \((P_{ref})\) of 30 kW when insulation level is 0.8 kV/m². At this insulation level, the SPV system could generate a maximum power \((P_{max})\) of 42 kW, indicating the sliding mode controller would be operating in power sufficient mode. At time \(t = 0.2\) sec, a step change from 30 kW to 20 kW in \(P_{ref}\) is given. Simulation results pertaining to the SPV power \((P_{pv})\) output from the solar array, the voltage output of the buck converter \((V_{dc})\),

<table>
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<tr>
<td>(K_v)</td>
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<td>(K_p)</td>
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<td>(K_i)</td>
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<td>Band limit for Hysteresis control</td>
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and inverter output current ($i_a$) waveforms are shown in Figure 4. It can be observed from the waveforms that sliding mode controller responds very quickly to the set point change and the controller achieved desired power balance.

5.2 Case-2: Operating in MPP Mode

Next, the sliding mode controller’s response to the power insufficient case is simulated. As in case-1, the system was initially operating under steady state condition with load demand ($P_{ref}$) of 30 kW when insulation level is 0.8 kW/m$^2$. At 0.2 sec $P_{ref}$ was suddenly changed from 30 kW to 50 kW. As stated earlier, for insulation level of 0.8 kW/m$^2$, $P_{max}$ is 42 kW. Thus, the purpose of this simulation case is to demonstrate ability of the controller to move from power sufficient mode to power insufficient mode dynamically. Figure 5 shows response of the system to sudden increase in load demand and its effect on $P_{pv}$, $V_{dc}$, and $i_a$. As can be seen from Figure 5, the sliding mode controller successfully switches from power sufficient mode to power insufficient mode and the system starts operating at MPP. As the power demand is more than $P_{act}$, the load network will draw remaining 8 kW power from the grid. It is important to note here that reactive power compensation can be also provided through VSI (CSI) in order to ensure only active power is drawn from the grid.

Thus the proposed strategy can also provide reactive power compensation and improve overall power quality at the PCC.

5.3 Case-3: Sudden Change in Climate Conditions

SPV systems may often encounter sudden climate changes, which may sometime lead to system instability. In this case, simulations were carried out to study the effects of varying
weather conditions by changing irradiation level. As in case-1, initially the system is operating at $P_{\text{ref}} = 30$ kW, with $\lambda = 0.8$ kW/m$^2$. At 0.2 sec irradiation level was changed from 0.8 kW/m$^2$ to 0.6 kW/m$^2$. As can be seen from Figure 6., the sliding mode controller performance is not affected by sudden climate change. In this case the controller was working in power sufficient mode during the simulation.

Controller can operate in islanded mode as well. In this case, a voltage controlled VSI (as opposed to current controlled VSI used in earlier cases) was used to transfer power from the SPV system to the PCC. The sliding mode controller was working in power sufficient mode during the simulation. It must be noted here that in islanded mode, the system can deliver a maximum power of $P_{\text{max}}$. However, if load demand is higher than $P_{\text{max}}$, the supervisory controller must make appropriate decision to prevent system collapse.

6. Conclusion

A power balancing sliding mode control strategy is proposed for grid-connected SPV systems. The main advantage of the proposed methodology is that back-up energy storage devices are not required for maintaining power balance and constant DC line voltage. Elimination of battery banks eliminates its maintenance and cost factor, this will improve overall SPV system power economy. The proposed sliding mode control algorithm can operate the buck converter in both the modes i.e. at maximum power point (power insufficient) and limited power point (power sufficient). The performance of the sliding mode controller demonstrated its effectiveness and applicability for grid-connected SPV systems under varying load and weather conditions.

7. References