A NOVEL MPPT CONTROLLED GRID-CONNECTED PHOTOVOLTAIC SYSTEM WITH DUAL FUNCTIONALITY OF ACTIVE POWER INJECTION AND REACTIVE POWER COMPENSATION IN A SINGLE PHASE SYSTEM

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Abstract: This paper deals with the study of integration of distributed generation with active power filtering functionality in a single- phase system. Here the active power generated by the photovoltaic (PV) system is injected into the grid system through a coupling capacitor whenever solar input is available and the remaining capacity of the power conditioning inverter is used to compensate for the reactive power demand. The control algorithm used in this paper is simple and easy to implement. The PV system is integrated through a novel and simple MPPT technique. The system is simulated and analyzed for a given non-linear load with and without renewable source at different atmospheric conditions using MATLAB/Simulink tool. The grid current becomes sinusoidal and in phase with the grid voltage and hence the source current THD is reduced to great extent.

Key words: active power filter, photovoltaic, maximum power point tracking, current controlled voltage source inverter.

1. Introduction

Grid – connected renewable power is the main path through which the energy fuel mix can be brought in line with the set goal of reducing carbon emissions. The distributed generation (DG) concept is becoming more and more popular as it can provide more reliability, reduced emissions and provide additional power quality benefits [1]. Solar energy, being abundant and widespread in its availability, is one of the attractive sources of energy. Unfortunately, PV generation system suffers from disadvantages such as poor conversion efficiency and nonlinear I-V characteristics. Hence it is required to extract maximum available power from the PV array. Several maximum power point tracking (MPPT) algorithms are reported in the literature [2]-[5]. When operated in grid connected mode the inverter is current controlled as the voltage at the point of common coupling (PCC) is imposed by the grid. Here the PV system injects only the active power to the grid through inverter and the reference current is computed from active power that PV system generates at a given time [6]. Several single-phase, single-stage grid interactive inverter topologies have been proposed [7], [8].

In the past few years, there has been considerable advancement in the field of power semiconductor technology. The intensive use of these devices in various applications has led to serious power quality issues. The regulatory commissions have specified acceptable harmonic levels that are allowed into the grid. To solve the power quality problems, active power filters (APF) are extensively used. Many APF topologies and control algorithms are reported in the literature [9]. The use of APF requires an additional cost. It is possible to integrate power quality functions by compensating the reactive power and the current harmonics drawn by the local non linear load into the grid - connected PV system just by modifying the control strategy to incorporate APF features [10].

In this paper, a single-phase, grid-interactive PV system with novel MPPT algorithm is proposed. The idea is to integrate PV system with shunt APF capabilities. Here the PV array is connected to the grid system with its inverter performing the additional function of APF besides real power injection. This is achieved with suitable modifications in the control algorithm without any additional hardware or power circuit for making the existing inverter to act as APF too. Hence the overall cost of the system is reduced. The single-
phase, grid interactive PV system along with its MPPT algorithm is modeled and simulated in MATLAB/Simulink environment. The results show that this PV system injects active power at the PCC and compensates for load reactive power. Hence the source/grid power factor is improved.

In this paper, section 2 describes the overall system description. Detailed PV system modeling with new MPPT method is explained in section 3. The control theory and the system modeling are covered in section 4 and 5 respectively. Section 6 covers design aspects of APF. The results and discussion are given in section 7 and conclusion is presented in section 8.

2. System Description

The system being studied is shown in figure 1. It consists of a current controlled voltage source inverter (CC-VSI) fed from a PV source. It fed current into the grid and the local load through a series connected filter inductance L. The output DC voltage of PV cell is maintained constant by capacitor Cdc at the input of the inverter as the power output of the inverter oscillates at twice the line frequency. Also it is required to connect a smoothing reactor in series with the local load to suppress the load current spikes.

![Fig. 1. Grid connected PV system](image)

3. PV Modeling and its Characteristics

The electrical output from the PV cell is described by the I-V characteristics. These I-V characteristics of solar cell can be obtained by drawing an equivalent circuit of the device as shown in the figure (2)[11],[12].

![Fig. 2. Equivalent circuit of PV module.](image)

The generation of current Iph by light is represented by a current generator in parallel with a diode which represents the p-n junction. The output current I is then equal to the difference between the light generated current Iph and the diode current Id. In practical applications, solar cells do not operate under the standard conditions. The two most important effects that must be allowed for are due to the variable temperature and irradiance.

The three most important electrical characteristics of a module are the short circuit current, open circuit voltage and the maximum power point as function of temperature and irradiance. To simulate PV array, the mathematical model neglecting shunt resistance Rs is used according to the following set of equations:

\[ V_c = \frac{A k T_c}{e} \ln \left( \frac{I_{ph} + I_d - I_c}{I_d} \right) - R_s I_c \]  \hspace{1cm} (1)

where, Ic and Vc are cell output current and voltage, respectively; Id is the reverse saturation current of the diode; Tc is the cell temperature at standard test conditions (STC) in °C; k is Boltzmann’s constant in J/K; e is electronic charge; Iph is the light-generated current; A=1.92 is ideality factor; Rs is the series resistance. The array voltage is obtained by multiplying equation (1) by the number of the cells connected in series, Nc. The current array is obtained by multiplying the cell current by the number of the cells connected in parallel, Np. This value of current is valid for a certain cell operating temperature Tc and its corresponding solar insolation level Sc. A method to include the effects of the changes in temperature and solar insolation levels is given in [13]. According to this, a model is obtained for known temperature (Tc) and solar insolation (Sc). The solar cell operating temperature varies as a function of solar insolation level and ambient temperature. The cell output voltage and cell photocurrent are affected by ambient temperature. These effects are represented by temperature coefficients CTV and CTI for cell output voltage and cell photocurrent respectively.

\[ C_{TV} = 1 + \beta_T (T_a - T_s) \] \hspace{1cm} (2)

\[ C_{TI} = 1 + \frac{T_r}{S_c} (T_s - T_a) \] \hspace{1cm} (3)
where $T_s$ and $S_s$ are ambient temperature and cell solar insolation level at STC, respectively. $T_s$ is any other temperature. $\beta_T$ and $Y_T$ are constants specified by the manufacturers. Similarly, the change in solar insolation level causes a change in the cell photocurrent and operating temperature. Therefore, the change in the cell output voltage and the cell photocurrent are corrected by the two factors,

$$C_{SV} = 1 + \beta_T \alpha_S (S_s - S_d)$$  \hspace{1cm} (4)\\
$$C_{SI} = 1 + \frac{1}{S_c} (S_s - S_d)$$  \hspace{1cm} (5)

where, $S_c$ is the new level of solar insolation. $\alpha_s$ represents the slope of the change in the solar insolation level. Using correction factors given in equations (2)-(5), the new values of cell output voltage $V_{cx}$ and photocurrent $I_{phx}$ are given for any temperature $T_s$ and solar insolation $S_s$ as

$$V_{cx} = C_{TV} C_{SV} V_c$$  \hspace{1cm} (6)\\
$$I_{phx} = C_{TI} C_{SI} I_{ph}$$  \hspace{1cm} (7)

where, $V_c$ and $I_{ph}$ are the cell output voltage and photocurrent at STC, respectively.

The rating of a PV module is estimated by the maximum power at STC which corresponds to an insolation level of 1000 W/m² and a cell temperature of 25°C. The PV cell manufacturers provide its characteristics by specifying the parameters given in table 1. Module: Solarex MSX60, 60 W PV module at STC irradiance: 1000W/sq.m, ambient temp: 25°C

<table>
<thead>
<tr>
<th>Table 1. Specifications for solar array at STC</th>
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<tbody>
<tr>
<td>$I_{sc}$</td>
</tr>
<tr>
<td>$V_{oc}$</td>
</tr>
<tr>
<td>$P_{m}$</td>
</tr>
<tr>
<td>$I_{m}$</td>
</tr>
<tr>
<td>$V_{m}$</td>
</tr>
</tbody>
</table>

Using equations (1)-(7) and the parameters at STC, the I-V and P-V characteristics of PV at different solar insolation and cell temperatures can be obtained as shown in figure (3) and figure (4).

### 3.1 Novel MPPT Technique

The maximum power point operation of a PV array is achieved by maximizing its output power to load. The maximum power must be determined for the changing temperature and solar irradiation level before it is compared with the operating power. The various MPPT methods used in the literature are based on the following methods [11]

1. Perturb & Observe (P&O)
2. Incremental conductance.

![Fig. 3. The I-V and P-V characteristics at different solar insolation at 25°C temperature.](image3)

![Fig. 4. The I-V and P-V characteristics at different cell temperature at 1000W/m² solar insolation.](image4)
Here, we propose a MPPT method based on open circuit voltage. Peak power point of the module is approximately at 76% of the module open circuit voltage. This value is fixed and does not vary much with the changes in the environmental conditions. By measuring the open circuit voltage at any given operating conditions and adjusting the module voltage to about 76% of $V_{oc}$ the peak power can be tracked. Using equation (6), $V_{oc}$ at any temperature and solar insolation is calculated. $V_{m}$ is approximated to 0.76 times this $V_{oc}$. Now using equation (1), $I_{m}$ and hence $P_{m}$ is calculated using iterative method.

4. Control Theory

In general, we can define the PCC voltage and current as in equations (8) and (9) respectively [10].

$$v_k(t) = V_d + \sum_{k=1}^{h} V_{mk} \sin(k\omega t + \phi_{mk})$$

$$i_k(t) = I_d + \sum_{k=1}^{n} I_{mk} \sin(k\omega t + \phi_{mk})$$

where $h$ and $n$ are the highest orders of harmonics in voltage and current, respectively. $V_{mk} = \text{peak value of the PCC voltage corresponding to the } k^{th} \text{ order harmonic.}$

$I_{mk} = \text{peak value of the load current corresponding to the } k^{th} \text{ order harmonic.}$

$V_d = \text{DC component present in the PCC voltage.}$

$I_d = \text{DC component present in the load current.}$

$\phi_{mk} = \text{phase angle of the PCC voltage corresponding to } k^{th} \text{ order harmonics.}$

$\phi_{mk} = \text{phase angles of the load current corresponding to } k^{th} \text{ order harmonics.}$

Figure (5) shows the phasor diagram of the proposed system of figure (1). In this figure, $V_c$, $V_L$, and $V_s$ are the rms voltages at grid, load and output of the inverter, respectively. $I_c$, $I_l$ and $I_s$ are the rms values of the currents from grid, to load and from the inverter, respectively. $I_{cp}$, $I_{lp}$ and $I_{cp}$ are the active components while $I_{cq}$, $I_{lq}$ and $I_{cq}$ are the reactive components of $I_c$, $I_l$ and $I_s$ respectively. The $\phi_{c}$ is the load power factor angle. The $\delta_s$ is the angle between $V_s$ and $V_c$. $\delta_s$ is the angle between $V_c$ and $V_L$. From $\Delta OAB$ in figure (5), voltage $V_{cl}$ across the filter inductor can be given as:

$$V_{cl}^2 = V_c^2 + V_L^2 - 2V_cV_L\cos\delta_s$$

Now neglecting filter resistance $R_s$, the current through inductor $I_c$ can be expressed as:

$$I_c \approx \frac{V_{cl}}{j\omega L_c}$$

Also, from inverter operation, we know that

$$V_c = m_aV_{dc}$$

where, $m_a$ is the modulation index. Now using equations (10), (11) and (12) the following equation is obtained:

$$I_c^2 = \frac{(m|V_{dc}|^2) + V_c^2 - 2(m|V_{dc}|V_L\cos\delta_s)}{(\omega L_c)^2}$$

From equation (13) it is clear that the magnitude of $I_c$ depends on ($m|V_{dc}|$) and ($\delta_s$). For optimal control at unity power factor compensation, the active power supplied by the grid at $k^{th}$ sampling instant should be equal to the grid apparent power $S_c(k)$. Hence

$$P_c(k) = P_{avg}(k) + P_c(k) - P_c(k) = \frac{V_m(k)I_m(k)}{2}$$

where, $P_{avg}(k)$, $P_s(k)$, $P_c(k)$ are the average load active power, output power of DC bus controller and ac side active power of the inverter at the $k^{th}$ sampling instant, respectively.

Using equation (14), the required peak value of the grid current can be calculated as

$$I_m(k) = \frac{2P_c(k)}{V_m(k)}$$

The instantaneous grid current is obtained by multiplying the peak value by unity sine vector.

$$i^*(k) = I_m(k)\sin(\omega k)$$
Further, the instantaneous grid current is compared with actual grid current \( (i_s) \) to get required compensating current, as:

\[
\Delta i_s(k) = i_s^*(k) - i_s(k)
\]

This current is given to a hysteresis comparator to generate PWM signals to drive the switches of CC-VSI.

5. System Modeling

Figure (6) shows the model of the proposed single-stage, single-phase grid interactive system. Here single-phase grid system is feeding a local non-linear load consisting of a diode rectifier bridge driving R-L load. At this load bus (PCC), a PV fed inverter is connected through filter inductor. This PV fed inverter consists of an IGBT driven H-bridge. The input DC voltage is the MPPT output voltage to this inverter.

![Fig.6. system model](image)

PV array is modeled separately with different combination of solar insolation and temperature using equations 1-7 as explained in section III. The output voltage corresponding to the maximum power is calculated and made available by the MPPT block as described in sub section novel MPPT technique.

The overall control is carried out by the controller block and the same is shown in figure (7). Here initially average load active power is extracted using two signals \( v_L \) and \( i_L \). The active power generated by the PV source is available at the MPPT output. The power loss in the DC-link voltage controller is to be subtracted from this PV active power. The grid active power hence is the net power required by the load minus the power available from the PV source. According to equation (15) then the peak value of source current is calculated. The unit sine wave is generated using load voltage signal and its peak value. The peak value of source current is multiplied by the unit sine vector as per equation (16). Hysteresis controller is used to generate the required pulses for the CC-VSI. The error signal is generated by comparing reference current with the actual source current.

6. Design of APF power circuit

6.1 Rating of switches used in CC-VSI

The power rating of the VSI is decided by the load current THD. It lies in the range of 20-50%. In this paper we have considered a 3kVA non-linear load with current THD of 26.87%. It is operated at 230V, 50 Hz system. It means, considering a tolerance factor of 2, IGBT switches of 25A are sufficient when the PV generated power is less than the load active power. But here we have to consider maximum PV generated power of 3600W. Hence the kVA capacity of inverter is increased to 3.8

### Table 2. Simulation parameters

<table>
<thead>
<tr>
<th>Location</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>Total no of modules</td>
<td>NsxNp=15x4=60</td>
</tr>
<tr>
<td></td>
<td>Maximum power generated by PV array</td>
<td>60x60 ≈ 3600 W</td>
</tr>
<tr>
<td>Active</td>
<td>Filter resistance and inductance</td>
<td>0.01Ω and 8mH</td>
</tr>
<tr>
<td>Power</td>
<td>DC-bus capacitance</td>
<td>5000 μF</td>
</tr>
<tr>
<td>Filter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grid</td>
<td>Grid voltage at 50 Hz</td>
<td>230 V</td>
</tr>
<tr>
<td>Load</td>
<td>Single-phase diode bridge with R-L load</td>
<td>( Z=(7.5+j7.8) ) Ω</td>
</tr>
</tbody>
</table>
kVA. Therefore IGBT switches to be used are of rating 32A (approximately 40A).

6.2 Sizing of DC bus Capacitor
The switching frequency must be chosen high enough to cancel harmonics up to a given frequency. The design of the filter inductor \( L_c \) and the DC bus voltage \( V_{dc} \) [14] are based on

(i) limiting the high frequency components of the injected currents; say 5% of the rated load current.

\[
\frac{I_{c.f.s}}{I_s} = \frac{V_{c.f.s}}{I_s(f_s/f)\omega L_c} < 5\% \quad (18)
\]

Where \( I_{c.f.s} \) is the rms value of the converter current at the switching frequency \( f_s \), \( V_{c.f.s} \) is the rms value of the converter output voltage at the switching frequency \( f_c \), \( I_s \) is the rms value of the fundamental load current.

(ii) the instantaneous \( \frac{di}{dt} \) generated by the active filter should be greater than the \( \frac{di}{dt} \) of the harmonic component of the load, so that the proper harmonic cancellation can take place.

\[
V_c \sqrt{2} + L_c \left( \frac{di}{dt} \right)_{load} < 0.5 \ V_{dc} \quad (19)
\]

Equations (18) and (19) allow the calculations of minimum values of \( L_c \) and \( V_{dc} \) independently. However, the selection of \( L_c \) and \( V_{dc} \) requires some sort of compromise. The converter must generate a high \( \frac{di}{dt} \) to cancel the harmonics. This requires small \( L_c \). But with small \( L_c \) ripple increases. Similarly higher \( V_{dc} \) gives more \( \frac{di}{dt} \) but at the cost of the increase in the current ripple.

The capacitor is designed to limit the DC voltage ripple to a specified value, typically 1 to 2%. The variation in DC voltage is given by

\[
\Delta V_{dc} = (v_{dc})_{max} - (v_{dc})_{min} = \Delta \left[ \sum v_{i_h}dt \right]_{load} \quad (20)
\]

For \( h=3,5 \ldots \ldots \) the percentage ripple of the DC bus voltage is defined as

\[
r_v = \frac{\Delta V_{dc}}{V_{dc}} \quad (21)
\]

From equations (20) and (21), the capacitor value is given by

\[
C = \frac{\Delta \left[ \sum v_{i_h}dt \right]}{r_v V_{dc}^2} \quad (22)
\]

For the given parameters of the system used in this paper the \( L_c \) and \( C \) is calculated as 8mH and 5000μF using equations (18)-(22).

7. Results and Discussions
The various parameters used for simulation are given in table 2. The operation of the system in different modes is summarized in the table 3. Figures (8), (9) and (10) show the operation of this system in different modes.

<table>
<thead>
<tr>
<th>Case</th>
<th>Time interval</th>
<th>Mode of operation</th>
<th>PV power injected</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0 - 0.1sec</td>
<td>Without APF and PV</td>
<td>0</td>
</tr>
<tr>
<td>II</td>
<td>0.1 - 0.2sec</td>
<td>APF</td>
<td>0</td>
</tr>
<tr>
<td>III</td>
<td>0.2 - 0.3sec</td>
<td>APF+PV</td>
<td>( &lt; P_L )</td>
</tr>
<tr>
<td>IV</td>
<td>0.3 - 0.4sec</td>
<td>APF+PV</td>
<td>( &gt; P_L )</td>
</tr>
</tbody>
</table>

Case I: Here the system operates without APF/PV power injection. From figure (8) it is clear that the source current is equal to load current. This can be seen from t=0 to t=0.1 sec. Figures (9) and (10) show that real and reactive demand of the load is supplied by the grid. The grid current and its THD are shown in figure (11).

Case II: at t=0.1sec, VSI is connected to the system with zero PV power generation. Now the VSI acts in pure APF mode. The reactive power demand of the load is supplied by the inverter as shown in figure (10). Now the grid current is near sinusoidal as clear from figures (8) and figure (12). The corresponding grid, VSI and load active power are shown in figure (9). There is slight increase in the grid active power demand as VSI draws fraction of active power to overcome inverter losses. The grid current and its THD are shown in figure (12) for this mode of operation.

Case III: at t=0.2 sec, the PV system generates power less than load active power demand. Now the grid current is reduced as part of the load current is shared by the PV source. As seen from figure (9), the grid active power is reduced by the same amount to that of the active power generated by the PV system. The remaining KVA capacity of the VSI is used to compensate for the reactive power demand of the load. Part of the reactive power is fed back to the grid due to line inductance.
This result can be seen in figure (10). The grid current remains near sinusoidal.

Case IV: at \( t=0.3 \) sec, the PV system generates power more than the load active power demand. The additional active power now is returned to the grid. This is clear from the reverse direction of grid current at this instant. The reactive power requirement is still maintained.

Fig. 8. Voltage and currents at different points

Fig. 9. Active power distribution

Fig. 10. Reactive power distribution

8. Conclusions

This paper presents the modeling and simulation of a grid connected PV system with APF functionality. The active power supplied by the PV system depending on environmental condition is injected into the grid. The local load active and reactive power is compensated by the PV system.
Hence this system behaves as an integration of active power source and APF with minimum hardware (as same VSI is used for real and reactive power injection) and simple control algorithm. The new simple MPPT algorithm is simulated in this paper. After compensation the grid current becomes sinusoidal and in phase with the voltage.

REFERENCES