A Novel Current Controlled Technique with Feed Forward DC Voltage Regulator for Grid Connected Solar PV System

Lakshmanan.S.A
School of Computing & Electrical Engg
Indian Institute of Technology Mandi
Mandi, India
lakshmanan_s_a@students.iitmandi.ac.in

Amit Jain
Power Systems Division
CPRI
India
amitlain@cpri.in

B. S. Rajpourohit
School of Computing & Electrical Engg
Indian Institute of Technology Mandi
Mandi, India
bsr@iitmandi.ac.in

Abstract—Solar energy is available in abundance and it is one of the most promising Renewable Energy Sources (RES) that can be used to produce electricity through Photovoltaic (PV) energy conversion process. Grid connected solar PV system is attracting more popularity due to the progress in the field of Power Electronic Converters (PEC) and various new control techniques. Different control techniques are used to control the Voltage Source Inverter (VSI) which is connected to the utility grid in order to achieve good power quality and to improve the dynamic response of the system. This paper proposes a novel current control technique with feed forward dc-voltage regulator for grid connected solar PV system. The feed forward dc-voltage regulator is used to remove the effect of nonlinear characteristics of the PV system and regulates the PV power and control the system dc link voltage. The performance index of the novel current control technique includes the low Total Harmonic Distortion (THD) level of the grid current and effective control of dc-link voltage. The proposed control technique is modeled and simulated in the MATLAB/Simulink location. Simulation results are presented to validate the performance of the proposed control technique.

Keywords—power electronic converter; total harmonic distortion; voltage source inverter;

I. INTRODUCTION

Increasing energy demand and the price of the fossil fuels as well as environmental pollution problem is putting pressure on the people to find sustainable solutions. So the interest in the Distributed Generation (DG) and green energy provided by RES like solar, wind are increasing. The solar PV system attracting more popularity due to the easy way of installation and less maintenance work. Due to the increasing rating of the solar PV plants, the power produced from the solar PV system is being fed into the electric grid via PEC. With continuous growth in the field of PEC and Digital Signal Processors (DSP), various new control techniques are proposed to control the VSI of the grid connected solar PV system [1]. Among the many control techniques, current control technique plays a major role to control the VSI. Basically the performance of the system depends on the value of the applied current control technique in order to achieve low THD and effective utilization of dc-link voltage. Ramp-Comparison is one of the current control technique which is used for PI compensators and fixed frequency triangular wave to generate Pulse Width Modulation (PWM) pulses for the inverter switches [2]. This method is very easy to implement, but the disadvantage is the highest value of phase tracking error and inherent amplitude variation. In Hysteresis current control technique, the output voltage level is switching between +Vdc to –Vdc based on the measured current goes below or above the tolerance boundary [2]. If it is a fixed hysteresis band over a fundamental switching period, the modulation frequency varies due to the periodic variation of grid voltage. Voltage Oriented Control (VOC) method is another current control technique and it is basically working on a synchronous rotating d-q frame. Actual d-q currents are able to lead by the infinite dc gain of the PI controller to the preferred values without introducing static error and achieved zero steady state error at the output current. VOC method is very sensitive with variation of load parameters, so the system stability is affected.

This paper proposes a novel current control technique with feed forward dc voltage regulator for grid connected solar PV system. The feed forward dc voltage regulator is used to reduce the effect of nonlinear characteristics of PV system and to control the system dc link voltage efficiently. The performance measures of the novel current control technique are low THD level of the grid current and utilization of the dc link voltage. In section II, the basic structure of the proposed grid connected solar PV system and modeling of solar PV system are explained and in section III novel current control technique with feed forward dc voltage regulator have been analyzed and in section IV Space Vector Pulse Width Modulation (SVPWM) technique is discussed, in section V simulation results are presented and last section presents conclusions.

II. CONTROL STRUCTURE OF GRID CONNECTED SOLAR PV SYSTEM

The grid connected solar PV system is shown in Fig. 1. First the PV system has been constructed by using PV arrays in which PV modules are connected in series and parallel to have a required amount of voltage and current levels. VSI is connected to the PV system via dc-link capacitor which maintains the dc-link voltage for the VSI.
Space Vector Pulse Width Modulation (SVPWM) technique is used to switch the VSI circuit. \( P_{\text{array}} \) is the PV array current and \( V_{dc} \) is dc link voltage which also called as PV array voltage. LC circuit is used as a filter to remove the harmonics produced by the VSI. Phase Lock Loop (PLL) is used for grid synchronization and it detects the phase angle, frequency and amplitude of the grid voltage.

### A. Modeling of PV system

Basically PV cell is a non-linear device and it can be represented by a current source parallel with diode [5]. PV modules and arrays are described by I-V and P-V characteristic curves. PV module photo current is given in (1).

\[
I_{\text{ph}} = I_{\text{sc}} + k[I(T - T_{\text{ref}})] \cdot \frac{\lambda}{1000}
\]

and output current of the PV array \( I_{\text{array}} \) is expressed as,

\[
I_{\text{array}} = N_{p} \cdot I_{\text{ph}} - N_{p} \cdot I_{\text{rs}} \left[ \exp \left( \frac{q \cdot V_{pp}}{k \cdot ATN_{s}} \right) - 1 \right]
\]

where \( I_{\text{rs}} \) is the reverse saturation current, \( q=1.6 \times 10^{-19} \text{C} \), \( k \) is the Boltzmann constant (138.15e-23J/K), \( T \) is the working temperature and \( \lambda \) is the solar irradiation level. From the shown in Fig. 1, the dc-link voltage is same as PV array output voltage.

So the output power \( P_{o} \) from the PV array is expressed as

\[
P_{o} = V_{dc} \cdot I_{\text{array}}
\]

Fig. 2, shows the P-V characteristics of the PV array system for different solar irradiation (\( \lambda \)) levels. It illustrates the variation of solar PV output power with respect to the dc-link voltage variation. The value of \( P_{o} \) is zero when \( V_{dc} \) is zero and its starts increasing when \( V_{dc} \) is increased. At particular value of \( V_{dc} \), the \( P_{o} \) reaches a maximum value and starts decreasing with further increasing of \( V_{dc} \).
At the inverter output side, the current can be described as

$$\frac{di_{inv}}{dt} = -RI_{inv} + \frac{v_{ter}}{L} - v_{inv}$$  \hspace{1cm} (8)

\(v_{inv}\) is the terminal voltage of the inverter and it can be described by the space vector signal \(\tilde{x}\) of the SVPWM switching scheme. So \(v_{inv}\) is,

$$v_{ter} = \frac{v_{dc}}{\sqrt{3}}$$  \hspace{1cm} (9)

Equation (7), (8) and (9) suggest that, dc-link voltage, thus in turn control the output power of a PV system by controlling the inverter output current.

III. NOVEL CURRENT CONTROL TECHNIQUE WITH FEED FORWARD DC VOLTAGE REGULATOR

The conventional current controller shown in Fig. 3. This controller is combined with the dc link voltage controller and current controller [7]. The reference voltage components produced from the controller is given in (10) and (11).

$$x_d = v_d - k_p x_d - k_i i_d + \omega L i_q$$  \hspace{1cm} (10)

$$x_q = v_q - k_p x_q - k_i i_q - \omega L i_d$$  \hspace{1cm} (11)

![Fig. 3. Conventional Current Control Technique](image)

The PWM switching signals for VSI is generated by transforming the d-q components to abc components and this signals are given to Sinusoidal Pulse Width Modulation (SPWM) block which is generating required pulse pattern for the inverter circuit.

The main objective of the proposed modified current controller with feed forward dc voltage regulator is to regulate the dc-link voltage and to achieve low THD in the grid voltage and current. In this novel current control structure, the error between the dc-link voltage and its reference value are processed by PI voltage regulator. The output of PI regulator is improved by feed forward voltage regulator to produce \(i_{dref}\). This \(i_{dref}\) is given to novel current controller block those enhance the \(i_d\) to track \(i_{dref}\). So by controlling the current \(i_d\), it is possible to control the output power of PV array and real power of the VSI output. Before started discussing about novel current controller, PLL circuit has been explained.

A. Synchronous Reference Frame PLL

PLL system is a feedback system with PI controller used to track the phase angle of the grid voltage [8]. Input to the PLL system is three phase grid voltage and the output is phase angle of the grid side voltage. The basic structure of SRF based PLL is shown in Fig. 4. The PLL system is having comparator which is giving the error signal to PI controller. The initial frequency \(\omega_0\) is added to the output of the PI controller and the resultant is giving estimated \(\omega'\).

![Fig. 4 Phase Lock Loop Structure](image)

The estimated phase angle of the grid voltage \(\theta\) is obtained by integrating the estimated frequency \(\omega\). The initial frequency is added to the output of the PI controller, to improve the dynamic performance of the system. Generally in the synchronous rotating frame, the real and reactive powers are calculated by,

$$P = \frac{3}{2} \text{Re}(v^dq(i^dq)) = \frac{3}{2} (v_d i_d + v_q i_q)$$  \hspace{1cm} (12)

$$Q = \frac{3}{2} \text{Im}(v^dq(i^dq)) = \frac{3}{2} (v_d i_q - v_q i_d)$$  \hspace{1cm} (13)

Reactive power is relative to \(i_q\). In order to make the reactive power is zero, the current \(i_{qref}\) is 0. So in the steady state the PV system is in unity power factor. When \(i_{qref} = 0\), the line vector aligned with d axis \(v_d=0\). So finally the real power and reactive power from the system are expressed as

$$P_s = \frac{3}{2} v_d i_d \quad \text{and} \quad Q_s = 0$$  \hspace{1cm} (14)

From (14), it is concluded that, the real power from the PV system is controlled by controlling the current \(i_d\).

B. Novel Current Control Technique

The proposed control structure is shown in Fig. 5. Based on equation (8), the control scheme has been designed. So based on that,

$$L \frac{di_d}{dt} = -R i_d + Loi_q + \frac{v_{dc}}{\sqrt{3}} x_d - v_d$$  \hspace{1cm} (15)

$$L \frac{di_q}{dt} = -R i_q - Loi_d + \frac{v_{dc}}{\sqrt{3}} x_q - v_q$$  \hspace{1cm} (16)

\(u_d\) is the output of the PI current controller, which is obtained from the error signal of \(i_d\) and \(i_{dref}\) and \(u_q\) is the output of the PI current controller which is obtained from the error signal of \(i_q\) and \(i_{qref}\) [9]. From the Fig. 5 the voltage components \(x_d\) and \(x_q\) are obtained as

$$x_d = \frac{\sqrt{3}}{v_{dc}} (u_d - Lo i_q + v_d)$$  \hspace{1cm} (17)

$$x_q = \frac{\sqrt{3}}{v_{dc}} (u_q + Lo i_d + v_q)$$  \hspace{1cm} (18)

Substituting equation (17) and (18) into equation (15) and (16),

$$L \frac{di_d}{dt} = -R i_d + u_d$$  \hspace{1cm} (19)

$$L \frac{di_q}{dt} = -R i_q + u_q$$  \hspace{1cm} (20)

The voltage components \(v_d\) and \(v_q\) are controlled by controlling \(i_d\) and \(i_q\). The \(x_d\) and \(x_q\) components are transformed into abc signals and sent to SVPWM block. Here SVPWM technique is used to produce required switching pulses for VSI. Internal Model Control (IMC) [12] method is used to design the PI controller and \(k_p\) and \(k_i\) values are obtained.
C. **Feed Forward DC Voltage Regulator**

The real power from the PV system and dc-link voltage is controlled by current $i_d$. So based on (6) and considering only The real power from the PV array and the PV system, the d-q frame based power balance equation is

$$\frac{1}{2} C \frac{dv_d^2}{dt} = P_{\text{array}} - \frac{3}{2} (v_d i_d)$$

(21)

The time constant of the current controller is very small, then $i_d \approx i_{dref}$, so the power balance equation can be expressed as,

$$\frac{1}{2} C \frac{dv_d^2}{dt} = P_{\text{array}} - \frac{3}{2} (v_d i_{dref})$$

(22)

Solar PV power is a non-linear function of dc-link voltage, temperature and irradiation levels. In order to consider the nonlinearities, a new approach is given for $i_{dref}$ [9] in (23).

$$i_{dref} = u_v + r P_{\text{array}}$$

(23)

Here $u_v$ is the control input, $r$ is the gain and it can be 1 or 0. Substituting $i_{dref}$ into equation (23), the power balance equation is expressed as,

$$\frac{1}{2} C \frac{dv_d^2}{dt} = (1-r)P_{\text{array}} - \frac{3}{2} (v_d u_v)$$

(24)

From the above equation, if $r=1$, then the collision of the PV characteristic on the dc-link voltage control is eliminated. So when $r=1$, the control system is together of an integrator and first order transfer function of current controller [14]. The transfer function is expressed as

$$\frac{i_d(s)}{i_{dref}(s)} = \frac{1}{r_s + 1}$$

(25)

IMC method is used to find the required parameters of the controller.

IV. **SPACE VECTOR PULSE WIDTH MODULATION**

SVPWM is employed to generate the desired output voltage vector $V$ in d-q reference frame. For a three phase VSI there are totally eight possible switching patterns and each of them determines a voltage space vector [15]. Fig. 6 which show space vector representation, eight voltage space vectors divide the entire vector space into six sectors namely 1-6. Except two zero vectors $V_0$ and $V_7$, all other active space vectors have same magnitude of $(2/3)V_{dc}$. In SVPWM, the reference voltage vector should be synthesized by the adjacent vectors of the located sector in order to minimize the switching times and to minimize the current harmonics.

The switching function $S_x(x=a,b,c)$ is defined as: If $S_x=1$, the upper switch is ON and lower switch is OFF. If $S_x=0$, the upper switch is OFF while the lower switch is ON. The eight vectors, called the basic space vectors include two zero vectors $V_0$ and $V_7$ and six non-zero $V_1$-$V_6$ vectors. Two zero vectors have zero magnitude and six non-zero vectors have the same amplitude as shown in Figure 6. The angle between any adjacent two non-zero vectors is 60 degrees.

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**Fig. 5 Proposed Novel Current Control Scheme with Feed Forward Voltage Controller**

**Fig. 6 SVPWM Sector Representation**
V. SIMULATION RESULTS AND DISCUSSION

MATLAB/Simulink based simulation model has been developed for grid connected solar PV system. Here the proposed current controller along with feed forward regulator is compared with a conventional controller in order to validate the performance indices. For that the 400V is considered as dc-link voltage and 230V is considered as a grid phase voltage with the frequency of 50Hz. The filter inductor and capacitor are 800$\mu$H and 400$\mu$F respectively. Controller parameters $k_p=0.0057$, $k_i=0.01$. The simulation result of the conventional current controller is shown in Fig. 7.

Fig. 7. Simulation results for the conventional current controller. (a) Inverter output line voltage (b) inverter current (c) grid phase voltage (d) grid current

In conventional controller, SPWM technique is used to switch the VSI. Fig. 7 (a) and (b) shows inverter output line voltage and output currents. Fig. 7 (d) and (c) shows waveforms of grid phase voltage and grid current. Both are following sinusoidal. The THD value of grid current waveform is shown in Fig. 8 and it shows that the THD value is 2.26%.

SVPWM based switching scheme is used for proposed current controller. The angle sector of SVPWM is shown in Fig. 9. The response of PLL for detecting phase angle of grid voltage for the proposed current controller is shown in Fig. 10. Simulation result of proposed current controller is shown in Fig. 11. Fig. 11 (a), (b) and (c) shows inverter phase voltage and line voltage and inverter current receptively. In Fig. 11 (d) and (e) grid current and voltage are given and both are following sinusoidal pattern.
The THD value of the grid current waveform is shown in Fig. 12 and it shows that the THD value is 1.35%.

From the simulations results it is understood that, THD level in the grid current is less in the proposed current controller compared to conventional current control technique and also the utilization of dc-link voltage is better as in the case of proposed current controller with feed forward dc voltage regulator and the impact of non-linear characteristics of PV system is also come to reduce under the proposed controller. The effective utilization of the dc-link voltage under the proposed controller is shown in Fig. 13.

VI. CONCLUSIONS

This paper proposed a novel current controller with feed forward voltage regulator for grid connected solar PV system. This control technique is compared with conventional current control technique. First the PV system is modeled and conventional current control technique is explained. Synchronous reference frame based Phase Lock Loop is described and design of novel current controller and feed forward voltage regulator has been analyzed. Both techniques are simulated using MATLAB/Simulink tool in order to validate the performance analysis. From the simulation results it is observed that, the proposed controller for grid connected solar PV system is efficiently controlling the dc link voltage and THD level of the grid current is less compared to the conventional controller and the PLL response is able to detect the phase angle of grid components under the proposed controller. The nonlinearity coming due to the PV system is also reduced by using the proposed feed forward based voltage regulator.

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