Abstract-In this paper, a current controller design method for a DC-AC inverter in a grid-connected photovoltaic or fuel cell power conditioning system (PCS) is proposed. A state feedback current controller using a sine reference function tracking algorithm and I-P (Integral-Proportional) outer DC-link voltage controller using a 120Hz notch filter are proposed to control the output current to be in-phase with the grid voltage and to regulate the input DC-link voltage. Since the analysis and design are performed in the time domain using the state equations, the current loop controller can be systematically designed for the required system specification using the pole placement technique. Also, the 120Hz notch filter for DC-link voltage regulation can enhance the dynamic performance by increasing the voltage loop bandwidth. The design guideline of each controller is provided using the stability analysis. For a design example, the prototype two-stage PCS hardware with a TMS320F2812 DSP and a real 200W solar array has been experimented to validate the proposed digital control scheme.

I. INTRODUCTION

In a grid connected solar array or fuel cell power system [1-3], a DC-AC inverter is essential and it has a current control loop to control the output current to be in-phase with the grid voltage for the high power factor, as shown in Fig.1. In the previous researches, a PI controller or a resonant controller is commonly used using the frequency domain analysis through the small signal modeling approach [4-7]. However these approaches require some iterative design procedure to satisfy the given time domain specifications because the design parameters in the frequency domain approach (such as bandwidth, phase/gain margins) are not directly related with the required performance (such as settling time, percent overshoot). A sine reference tracking state feedback current controller using the pole placement technique is proposed in this paper. Since the analysis and design are performed in the time domain, the current loop controller can be systematically designed for the required system specification [8-11]. Also, a method to improve a dynamic performance of DC voltage control loop, especially the photovoltaic PCS application, is introduced using a notch filter. This scheme can increase the bandwidth of voltage control loop maintaining the current control loop performance. Usually, the bandwidth of the conventional voltage control loop is limited about 10Hz due to the inherent 120/100Hz ripple voltage caused by the grid AC voltage. For a design example of the proposed control scheme, a prototype two stage grid connected photovoltaic PCS has been built and tested using a real solar array.

II. SYSTEM DESCRIPTIONS

In grid connected solar array system, two stage PCS schemes have been developed without the bulky 50/60Hz step-up transformer in residential applications (below 10kW). These schemes have the advantages of wide solar array operating range, low inverter current, reduced filter size, and small overall size and hence can be integrated into one module. The typical two stage grid connected photovoltaic PCS is shown in Fig. 1. The boost converter controls the solar array operating point, and the post single stage inverter controls the DC link capacitor voltage and controls the output current to be in-phase with the grid voltage for the high power factor. Also, the boost converter performs the maximum power point tracking (MPPT) control by regulating the solar array voltage or current to the reference value generated by the MPP tracker. The phase-locked-loop (PLL) control method is also included in the post stage inverter control loop. This loop detects the phase angle of the grid voltage, and then generates the reference voltage of the inverter current control with the output of the DC link voltage control loop. After introducing the proposed current control algorithm for the inverter, the remained control algorithms, which are used in the design example and experiment, will be briefly introduced in this paper.

III. PROPOSED DIGITAL STATE FEEDBACK CURRENT CONTROLLER FOR SINE REFERENCE TRACKING CONTROL IN THE GRID CONNECTED INVERTER

A current controller of the grid connected inverter controls
the output current of inverter to be in-phase with the grid voltage, which has a sine wave form \( I_{\text{ref}} = a \cdot \sin(\omega t) \) generated by a voltage controller and PLL controller. Fig. 2 shows a grid connected single-phase inverter model with the bi-polar switching method. In case of other switching methods, such as the uni-polar switching etc., the proposed control scheme can be applied through the similar procedure. The averaged large signal inverter model is derived using the un-terminated modeling. The DC link voltage is assumed constant during one switching period \( V_{\text{dc}} = V_{\text{dc}} \).

\[
\begin{align*}
\dot{i}_d(t) &= \frac{2V_{\text{dc}}}{L} d(t) - \frac{V_{\text{dc}}}{L} V_g(t) \\
\dot{x}(t) &= Ax(t) + B_1 d(t) + B_2 v_g(t) + B_3 y(t) = Cx(t) \\
\end{align*}
\]  

where \( A \), \( B_1 = \frac{2V_{\text{dc}}}{L} \), \( B_2 = -\frac{1}{L} \), \( B_3 = -\frac{V_{\text{dc}}}{L} \) and \( C = 1 \), 

where, a state and an input voltage are \( x(t) = i_d(t) \), \( v_g(t) = b \cdot \sin(\omega t) \) respectively. The objective is to design an overall system such that the output, \( y(t) \), will track asymptotically a sine reference input, \( I_{\text{ref}} = a \cdot \sin(\omega t) \), even with the presence of an input disturbance and with plant parameter variations. Let an error state, \( e(t) \), and augmented state variables, \( z(t) \), \( u(t) \), be defined as

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + B_1 d(t) + B_2 v_g(t) \\
\dot{z}(t) &= \omega^2 x(t) + \dot{x}(t) \\
u(t) &= \omega^2 d(t) + \dot{d}(t) + \frac{B_2}{B_1} \omega^2 \\
e(t) &= I_{\text{ref}}(t) - y(t) \\
\end{align*}
\]

Then, the system can be expanded by the augmented state vector \([e(t) \hspace{1cm} z(t)]^T\).

\[
\begin{pmatrix}
\dot{e}(t) \\
\dot{z}(t)
\end{pmatrix} =
\begin{bmatrix}
0 & I & 0 \\
0 & 0 & A
\end{bmatrix}
\begin{pmatrix}
e(t) \\
z(t)
\end{pmatrix} + 
\begin{bmatrix}
0 \\
0
\end{bmatrix} u(t)
\]

\[
\begin{pmatrix}
e(t) \\
z(t)
\end{pmatrix} =
\begin{cases}
0 \\
-\omega^2
\end{cases}
\]

\[
\omega^2 = C \\
\gamma = \omega^2 \frac{\partial m}{\partial \omega^2}
\]

If the expanded system is controllable, then there exists a state feedback gains, \([K_1 \hspace{1cm} K_2 \hspace{1cm} K_3] \), such that the expanded system is stable. That means the output current of the inverter tracks the sine reference value to be in-phase with the grid voltage for the high power factor. Furthermore, the system’s eigenvalues can be placed to the desired poles, from which the state feedback gains are determined.

The augmented state equation becomes a 3rd order system. Thus, using the dominant pole approach for the pole placement technique [12], the desired pole locations can be easily obtained relating the given specification and the general 2nd order system’s response.

Settling time \( \equiv -\frac{4}{\delta^2 \omega_n} \leq T_{\text{set}} \) [sec]

Percent overshoot \( \equiv 100 \exp \left( -\frac{\frac{\delta^2 \pi}{\sqrt{1-\delta^2}}}{\omega_n \delta} \right) \) \( \leq P.O. \) [%]

\[
\begin{pmatrix}
\omega_n & < s + \omega_n \\
\omega_n & > 0
\end{pmatrix} \Rightarrow \omega_n = \lambda_{\text{spec}} \omega_n \\
\]

Fig. 3 shows the allowed region of the desired pole locations. The natural frequency of the closed loop system, \( \omega_n \), should be located above 50/60Hz to track the sine reference voltage and is limited below the half of switching frequency due to the inherent characteristic of switching system.
Using this pole placement technique, the feedback controller for the system can be designed. The equivalent discrete transformation using Euler’s method is applied to realize the proposed control scheme in a digital controller, such as DSP, FPGA, and Microcontroller etc.. Using the Laplace transformation, the duty ratio can be derived from equation (2) and (3), and Fig. 4 shows the complete control scheme. The three terms in equation (5) can be realized in the state equations for the controller implementation.

\[ u(t) = -K_e e(t) - K_i \dot{e}(t) - K_s \omega^2 x(t) - K_i \ddot{x}(t) = \omega^2 \ddot{x}(t) + \dot{d}(t) - \frac{\omega^2}{2} \]

\[ D(s) = \frac{K_s + K_i}{s^2 + \omega^2} e(s) - K_x X(s) + \frac{\omega^2}{2} \frac{1}{s^2 (y^2 + \omega^2)} \]

\[ D_i(s) \Leftrightarrow \begin{bmatrix} \dot{p}(t) \\ \dot{\theta}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega^2 & 0 \end{bmatrix} \begin{bmatrix} p(t) \\ \theta(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} e(t) \]

\[ d_i(t) = -K_i \begin{bmatrix} p(t) \\ \theta(t) \end{bmatrix} \]

\[ D_i(s) \Leftrightarrow d_i(t) = -K_i \omega^2 x(t) \]

\[ D(s) \Leftrightarrow d_i(t) = \frac{1}{2} [1 - \cos(\omega t)] \]

IV. DESIGN EXAMPLE

To verify the theoretical analysis, the proposed current control scheme has been tested with the prototype two stage photovoltaic power conditioning system, as shown in Fig. 5, for a design example. Due to the limitation of the solar array’s power in laboratory, the reduced voltage scale implementation for a design example. Due to the limitation of the solar array’s photovoltaic power conditioning system, as shown in Fig. 5, control scheme has been tested with the prototype two stage array stabilizing control simultaneously. Also, the advanced controller and can achieve parallel module control and solar array stabilizing control simultaneously. Therefore, the advanced controller can achieve parallel module control and solar array stabilizing control simultaneously.

Incremental conductance maximum power point tracking (MPPT) algorithm is used in the proposed system [14]. This approach has the advantages of good accuracy around the MPP and fast tracking speed due to the variable step size, which is based on the inherent characteristic of the solar array.

B. Phase-Locked-Loop (PLL) Control using D-Q transformation and All-Pass-Filter (APF)

The PLL controller using the D-Q transformation and the APF is designed as shown in Fig. 6. The feedback signal, \( v_f \), is calculated with the estimated angle, \( \theta_e \), and the grid voltage, \( v_g = b \cdot \sin(\omega t) = b \cdot \sin \theta \).

\[
\begin{align*}
\dot{v}_{cl,app} &= -s + \omega \theta_e v_c = -b \cdot \cos \theta \\
\begin{bmatrix} v_d \\ v_q \end{bmatrix} &= \begin{bmatrix} \cos \theta_e & \sin \theta_e \\ -\sin \theta_e & \cos \theta_e \end{bmatrix} \begin{bmatrix} v_{cl,app} \\ v_g \end{bmatrix} = \begin{bmatrix} 0 \\ -b \end{bmatrix} \text{ if } \theta_e = \theta \\
\therefore v_d = -b \cdot \sin(\theta_e - \theta_e) = b(\theta_e - \theta) 
\end{align*}
\]

The bandwidth of the PI controller is designed as 20Hz.

\[
\theta_e(s) = \frac{b k_d s + b k_i}{s^2 + b k_d s + b k_i} \tag{10}
\]

C. DC-link I-P voltage controller

The grid connected inverter with a output current controller...
may become unstable according to the input source type of the inverter, which has a current source characteristic, such as the solar array current source region and the diode current of the pre-stage boost converter [15-16]. Thus, the voltage controller should be designed that the unstable plant is to be stable using the nyquist criteria or the root locus approach. Fig. 7 shows the I-P voltage controller with a Notch filter. The I-P voltage controller is frequently used when the voltage overshoot performance is important. Also, the Notch filter for the DC link voltage regulation is introduced to enhance the dynamic performance. Since the Notch filter reduces the $2\omega$ frequency ripple of the DC link voltage caused by the grid voltage and the current controller, the voltage control loop bandwidth can be increased.

D. Digital Signal Processor Approach

Fig. 8 depicts the PWM duty ratio generation and the exact sampling frequency generation using the synchronous PWM as well as the average inductor current sampling method without the use of a sensing-signal-conditioning filter. Taking into account the A/D conversion time and the control algorithm calculation time, the duty cycle is updated at the next sampling time. This provision reduces control delays in the feedback loop.

V. EXPERIMENTAL RESULTS

Fig. 9 and 10 show the MPPT loop tracking speed and performance during the startup transition and when the illumination is continuously decreased. Fig. 11 illustrates the transient response when the illumination level is stepped down. Fig. 12 shows the inverter output current (Enlarged waveform of Fig. 11). It is confirmed that the proposed sine reference
tracking state feedback controller can achieve the inverter current control to be in-phase with the grid voltage, showing a good power factor. Fig. 13 and 14 show the performance of the I-P voltage controller without the Notch filter, which has 3Hz bandwidth of voltage loop gain. Even though the bandwidth of the voltage controller is lower than that of the proposed voltage controller (12Hz), the performance of the system is poor (voltage deviation level and distorted current waveform) because 120Hz ripple at DC link voltage cannot be suppressed enough by the voltage controller and due to the lower bandwidth of the voltage controller.

VI. CONCLUSION

A sine reference tracking state feedback current control approach using the pole placement technique is proposed. Since the analysis and design is performed in the time domain using state equations, the controller can be systematically designed for the required system specification. Also, a Notch filter in the DC link voltage control loop is introduced to improve dynamic performance of the proposed control system. For a design example and verification of proposed control scheme, a prototype two stage grid connected photovoltaic PCS hardware has been built and tested. The design guideline and stability issue of each controller are discussed to implement the proposed two stage PCS control scheme as well.

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