Controller Design and By-Pass Structure for the Two-Stage Grid-Connected Photovoltaic Power Conditioning System

Seongjun Lee, Hyunsu Bae and B.H. Cho

SEOUL NATIONAL UNIVERSITY

DEPARTMENT OF ELECTRICAL ENGINEERING, SAN 56-1, SILLIM-DONG, GWANAK-GU, SEOUL 151-742

Abstract

In this paper, a systematical controller design method for a two-stage grid-connected photovoltaic power conditioning system is proposed. For a pre-stage boost converter to achieve the stable operation in the entire region of solar array, the digital resistive current mode controller is used. This algorithm is very simple to implement with a digital controller and there is no power stage parameter dependency in the controller design. For a post-stage single-phase full-bridge inverter, a PI controller with a feed-forward compensation for the inner current control is employed. Furthermore, in case that the operating point of the solar array under varying environmental conditions is higher than the required voltage for the inverter current control, the bypass mode for the boost converter is possible for the more efficient operation. The proposed control scheme is validated through the experiment of the prototype two-stage power conditioning system hardware with a 200W solar array.

1. Introduction

Concern for developing alternative energy systems has been increasing continuously. Among renewable energy sources, the solar energy is one of the promising solutions because it produces the electrical power without inducing the environmental pollution. Many studies on the developing grid-connected photovoltaic power conditioning system (PV PCS) have been completed [1, 2].

In grid-connected PV system, two-stage PCS schemes have been developed without the bulky low-frequency transformer. These schemes have advantages of wide solar array (SA) operating range, small overall size and weight. The conventional two-stage grid-connected PV PCS is shown in Fig. 1. The boost converter aims to control the solar array operating point for obtaining the maximum power, and the one of two main tasks of the single-phase inverter is to control the DC-link voltage and the other is to control the output current to be in-phase with the grid voltage for the unity power factor.

In this paper, a systematical controller design method for a two-stage grid-connected photovoltaic PCS is proposed. For a pre-stage boost converter to achieve the stable operation of the entire SA operating ranges, the digital resistive current mode controller is used. The effective input impedance characteristic of the converter seen by the SA is controlled as a resistive sink using a simple nonlinear transformation algorithm. This algorithm strongly guarantees the stable operation of the SA under environmental variations, compared with a SA voltage or current control [3]. For a post-stage single-phase full-bridge inverter control, a PI controller with feed forward compensation for the inner current control and the outer DC link voltage control is designed systematically in order to control the grid current in phase with the utility grid and to stabilize the DC-link voltage through the unterminated small signal modeling technique. Furthermore, in case that the operating point of the SA under varying environmental conditions is higher than the required voltage for the inverter current control, the bypass mode of the boost converter is possible for the more efficient operation. The proposed control scheme is validated through the experiment of the prototype scaled-down two-stage PCS hardware with a 200W solar array.

2. Control Methods of Two-Stage Grid-connected Photovoltaic Power Conditioning System

The proposed hardware prototype of the two-stage grid-connected photovoltaic PCS is shown in Fig. 2. The proposed digital control algorithm and the detailed controller structure are listed below.

2.1 Digital resistive current mode control algorithm for the boost converter

If the effective load characteristic of the boost converter seen by the SA is a resistive load sink, r_z, the boost converter input current, i_{Lcon}, and the SA voltage, v_{sa}, have the relation of (1).

$$v_{sa} = i_{Lcon} \cdot r_z \tag{1}$$

where, r_z is the equivalent resistance of the boost converter.

Since the boost converter is operated in the continuous conduction mode during the MPPT control, the control duty ratio to realize the current mode control can be derived as (2) based on the DC gain of boost converter.

$$v_{sa} = d_c' \cdot v_{dc} = i_{Lcon} \cdot r_z \quad \Leftrightarrow \quad d_c' = \frac{i_{Lcon} \cdot r_z}{v_{dc}} \tag{2}$$

2.2 Controller design for the grid-connected single-phase inverter

The single-phase full bridge inverter is controlled as switching states, such as S_a and S_b which control the upper switch of each legs as shown in Fig. 2. Assuming that the carrier switching frequency is higher than that of the modulating signal, the switching states are represented as duty ratios, d and 1-d, respectively. Thus, the average state equations can be derived as (3).

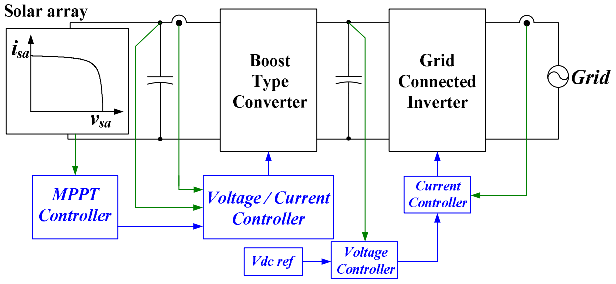

Fig. 1 The conventional two-stage grid-connected photovoltaic power conditioning system control scheme

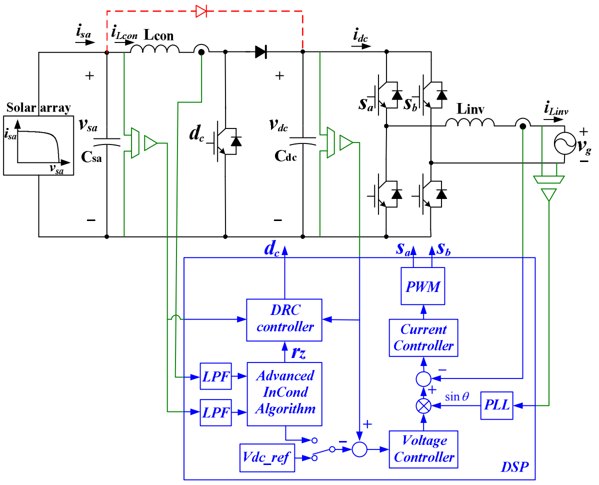

Fig. 2 The proposed prototype PCS experimental hardware and control

$$\frac{di_{Linv}}{dt}=\frac{(2d-1)}{L_{inv}}v_{dc}-\frac{1}{L_{inv}}v_g\,,\quad \frac{dv_{dc}}{dt}=\frac{i_i}{C_{dc}}-\frac{(2d-1)}{C_{dc}}i_{Linv} \tag{3}$$

For closing the inner current-loop, assuming that the DC-link voltage is sustained during one switching period, the PI current controller is employed for the required performance and stability as shown in Fig. 3. However, the classical PI controller induces the magnitude and phase errors due to the large variation of the grid voltage. Thus, the feed-forward compensation is used in order to reject the disturbance and the small signal equation of the feed-forward algorithm is derived as (4). As shown in Fig. 4 using parameters in Table 1, the effect of the grid current to the grid voltage is greatly alleviated.

$$d_{ff}=\frac{1}{2}\left(1+\frac{v_g}{v_{dc}}\right)\ \Rightarrow\ \hat{d}_{ff}=-\frac{1}{2}\frac{V_g}{V_{dc}^{\,2}}\hat{v}_{dc}+\frac{1}{2}\frac{1}{V_{dc}}\hat{v}_g \tag{4}$$

After the current loop is closed, the DC-link voltage controller is designed in order to stabilize the current loop closed system. However, because the current-loop closed plant, which means the inductor current reference to DC link voltage transfer function of Fig. 5, has a right-half-plane pole [4], the voltage controller, Hv(z), should be designed in order to push the unstable pole into the unit circle using Nyquist stability criterion or Root-locus. The designed voltage control-loop based on the experimental parameters has a low-frequency bandwidth under 10Hz and the stability is insured through the Nyquist plot of Fig. 6. The power stage transfer functions of the Fig. 5 are derived through the small signal modeling technique as (5).

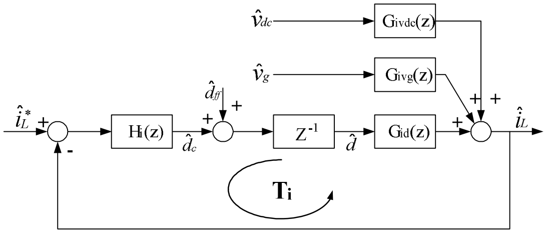

Fig. 3 Control block diagram for grid current control

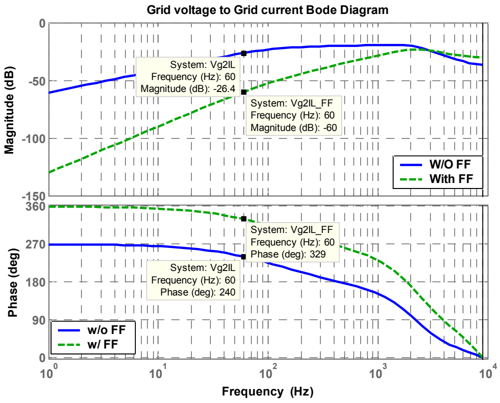

Fig. 4 Effect of the inductor current to grid disturbance with feed-forward

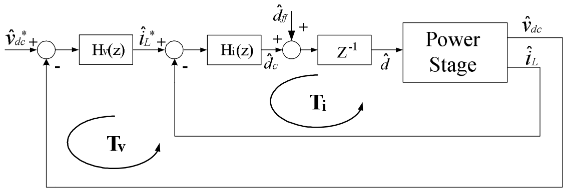

Fig. 5 Control block diagram for two-loop control

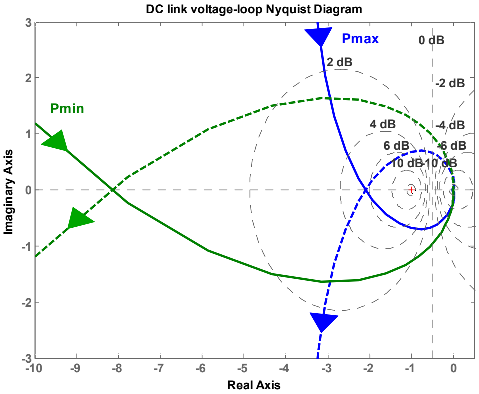

Fig. 6 Nyquist plot of the DC-link voltage-loop

$$\frac{\hat{i}_L}{\hat{d}}=-\frac{2I_L}{2D-1}\frac{1-s/\omega_{z1}}{1+s^2/\omega_o^{\,2}}\,,\quad \frac{\hat{v}_{dc}}{\hat{d}}=-\frac{2V_{dc}}{2D-1}\frac{1+s/\omega_{z2}}{1+s^2/\omega_o^{\,2}} \tag{5}$$

$$\text{where,}\quad \omega_o=\frac{2D-1}{\sqrt{LC}},\quad \omega_{z1}=\frac{(2D-1)I_L}{CV_{dc}},\quad \omega_{z2}=\frac{(2D-1)V_{dc}}{LI_L}$$

2.3 Bypass mode of the two-stage PCS

The boost converter has a function of the voltage booting. However, if the operating point of the solar array is higher than the required DC-link voltage, the boost converter does not need to operate. Thus, because the two-stage PV PCS becomes a single-stage grid-connected full-bridge inverter, more efficient operation is possible. However, the power stage of the boost converter is transformed into LC filter between the solar array and inverter. Then the stability problem of the existing system is issued due to adding the LC filter.

For analyzing the stability of the single-phase inverter with LC filter, the impedance ratio between the closed-loop inverter input impedance and the output impedance of the filter including the SA is identified. From Fig.7, the interaction can occur at the current source region of the solar array because adding the LC filter has a change of the existing system loop-gain at the resonant frequency of the input filter. This may cause a instability problem of the system. In order to avoid this interaction during the bypass mode, one of possible ways is to add the damping network or bypass diode.

3. Experimental Results

To verify the proposed control scheme, the scaled-down experiments are carried out due to the limitation of the solar array in the laboratory. The parameters of the power stage are tabulated in Table I. Figure 8 shows the MPPT loop tracking performance

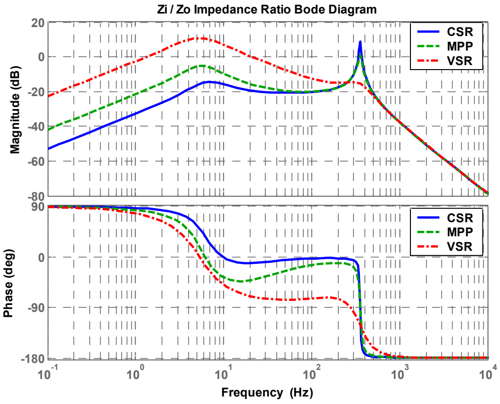

Fig. 7 Impedance ratio between output impedance and closed input impedance at the interface

TABLE 1. PARAMETERS OF THE POWER STAGE

Solar Array (Symphony Energy SE-S 173, Two modules)	
One module operating voltage	0-40V
Illumination System (HID Lamp)	
Inductor	Lcon = 1mH, Linv = 1.5mH, Cf = 2.2uF
Capacitor	Csa = 200uF, Cdc = 2200uF
Grid & DC-link voltage	22Vrms, 45Vdc
Switching Frequency	Fs,con = 18kHz, Fs,inv = 9kHz
DSP	TMS320F2812

during the startup and the bypass mode operation. Without the damping, the oscillation occurs during the mode change transient as shown in Fig. 9. In our case, the oscillation is gradually decreased due to the leakage components, such as equivalent series resistance of the capacitor and inductor, of the power stage. Since the resonant frequency of the LC filter is much higher than the designed DC-link voltage-loop bandwidth, the stability of the system is insured. However, at the startup of the bypass mode, the resonant phenomena in the LC filter are observed. Thus, in order to achieve more efficient and stable performance, the bypass diode can be added to an extra branch paralleled with boost inductor and diode, as the dashed line of Fig. 2. Figure 10 shows the waveforms of the adding the bypass diode.

4. Conclusions

A systematical controller design approach of the two-stage grid-connected photovoltaic power conditioning system is proposed in this paper. The simple nonlinear transformation algorithm is used for the solar array stabilizing control of the pre-stage boost converter. For a post-stage single-phase full-bridge inverter control, a PI controller with a feedforward compensation for the inner current control and the outer DC link voltage control is designed in order to control the grid current to be in phase with the utility grid and to stabilize the DC-link voltage through the unterminated small signal modeling technique. Furthermore, in case that the operating point of the SA under varying environmental conditions is higher than the required voltage for the inverter current control, the bypass mode of the boost converter is proposed for the more efficient operation. For the verification of the proposed digital control scheme, 200W scaled-down prototype two-stage hardware has been built and tested.

Acknowledgment

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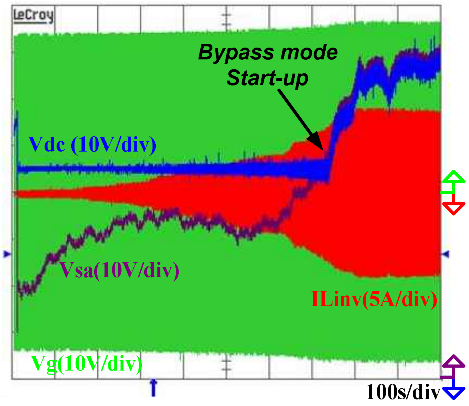

Fig. 8 Performance of the PCS during the startup transition

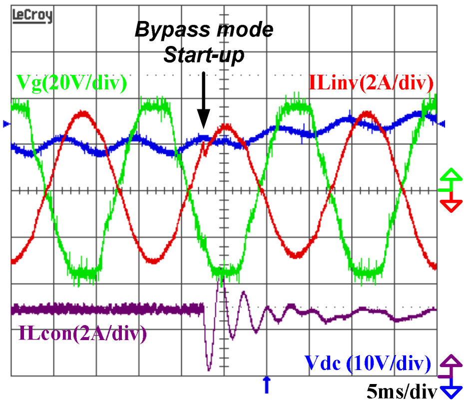

Fig. 9 The waveforms during mode change

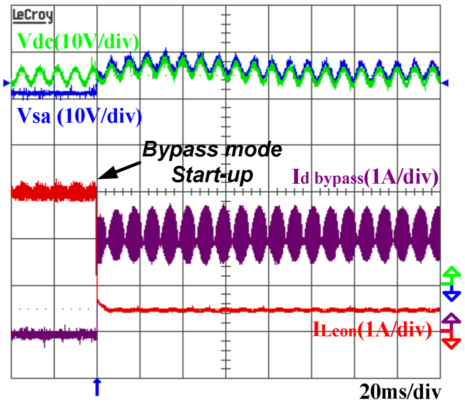

Fig. 10 The waveforms during mode change with an extra branch

Reference

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