Mitigation of Low Frequency AC Ripple in Single-Phase Photovoltaic Power Conditioning Systems

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Abstract

A photovoltaic power conditioning system (PV PCS) that contains single-phase dc/ac inverters tends to draw an ac ripple current at twice the output frequency. Such a ripple current perturbs the operating points of solar cells continuously and it may reduce the efficiency of the current based maximum power point tracking technique (CMPPT). In this paper, the ripple current generation in a dc link and boost inductor is analyzed using the ac equivalent circuit of a dc/dc boost converter. A new feed-forward ripple current compensation method to incorporate a current control loop into a dc/dc converter for ripple reduction is proposed. The proposed feed-forward compensation method is verified by simulation and experimental results. These results show a 41.8 % reduction in the peak-to-peak ac ripple. In addition, the dc/ac inverter control system uses an automatic voltage regulation (AVR) function to mitigate the ac ripple voltage effect in the dc link. A 3kW PV PCS prototype has been built and its experimental results are given to verify the effectiveness of the proposed method.

Key Words: Automatic voltage regulation, Current based maximum power point tracking, DC/DC converter, Feed-forward ripple current compensation method, Ripple reduction

I. INTRODUCTION

Photovoltaic (PV) energy is currently considered to be one of the most useful renewable natural energy sources in the world. However, in the literature, the energy-conversion efficiency of PV arrays is still low, and thus, the maximum power point tracking (MPPT) control technique is required to extract the maximum power from a PV array in order to achieve maximum operating efficiency. Most photovoltaic power conditioning systems (PV PCS) are adapted to voltage based maximum power point tracking (VMPPT) where the voltage reference is generated by dc/dc converter control with incremental conductance or the perturbation and observation method (P&O). But VMPPT generates perturbation ripples in the maximum power point (MPP) because of the 2nd-order harmonic ripple reflection and MPPT control perturbation. Therefore MPPT efficiency is reduced by ripples and noise. The proposed current based maximum power point tracking technique (CMPPT) [1] uses a current reference with the modified incremental conductance method. The advantage of CMPPT control has been verified. CMPPT can reduce ripple and achieve the MPP accurately. Therefore the system

Fig. 1. Block diagram of a single phase PV PCS.

Fig. 2. Transformer-less type PV PCS.

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efficiency can be increased. However, the CMPPT also reflects a 2nd-order harmonic ripple to achieve the MPP, which is why a low-frequency ac ripple mitigation method is proposed in this paper.

Fig. 3. Dc/ac inverter.

Fig. 4. Dc-Link voltage and current with ripples.

Fig. 1 shows the block diagram of a PCS that contains a dc/dc boost converter and a dc/ac inverter. The output of the dc/dc converter voltage (the input of dc/ac inverter in the dc-link capacitor) is 380V and the output of the dc/ac inverter is 220V/60Hz of grid voltage. The dc/ac inverter converts dc-link voltage to ac voltage in order to transfer solar energy to grid voltage. With a linear load, the output current has the same frequency phase and sinusoidal waveform as the grid voltage.

The inverter input voltage and current in the dc link are dc, but the current contains high frequency switching noises and a low frequency ripple component. It contains a 120 Hz component as shown in Fig. 1. The frequency of the ripple component is 120Hz, which is twice the output frequency. The output current undergoes a rectification effect through the inverter switches, and thus it appears to be a 120Hz pulsating current. The 120Hz pulsating current is smoothly filtered by the dc link capacitor but a significant part of the 120Hz ripple continues to propagate through the dc/dc converter and finally the solar cells.

Although PV PCS control has been studied for about three decades, a good control method for 120Hz ripple reduction has not been found for application to a single phase PV PCS. Recently, Dr. Lai proposed an active control technique to reduce ac ripple for fuel cell applications [2], [3]. A 120Hz pulsating current also generates a 120Hz ripple voltage on the dc link voltage, which causes a distorted ac output current. Reducing the ripple voltage by a programmed pulse-width modulation (PWM) has been proposed [4] and ripple-free dc-link voltage was achieved at the expense of large dc-link filter component values [5].

In this paper, a new control method for reducing the 120Hz ripple current, which is propagating into a dc/dc converter, is proposed for dc/dc converters. Also an automatic voltage regulation (AVR) function is employed for dc/ac inverters. Because the 120Hz ripple current perturbs the operating points of solar cells, it degrades the MPPT function of a PV PCS and therefore, decreases the MPPT efficiency along with

Fig. 5. Dc/dc boost converter (ripple free dc-link).

Fig. 6. Duty cycle D generation (ripple free dc link).

the entire PCS operation efficiency [6], [7]. Therefore, the proposed control method can increase the operation efficiency. This paper details an analysis of the proposed method. Its feasibilities are verified by simulation and experiments with a 3kW PV PCS.

II. PROPOSED AC RIPPLE MITIGATION METHOD

Fig. 2 shows a commonly used transformer-less type PV PCS for residential use. The PCS is composed of a PV array, a dc/dc boost converter, a dc-link, a dc/ac inverter and an L-C-L filter. PV voltage V_{pv} has a wide voltage range, from 150V to 400V, dc/dc boost converter regulated PV current I_{pv} , in order to perform a MPPT function. The dc/ac inverter is controlled to generate the grid current with a unity power factor.

A. AC ripple generation in a DC-link

Fig. 3 shows a single-phase full bridge dc/ac inverter, where the dc-link power from the capacitor C_d is used to generate the ac grid V_{ac} . The grid voltage V_{ac} and grid current I_{ac} are defined as follows:

$$V_{ac} = V_m \sin \omega t \quad (1)$$

$$I_{ac} = I_m \sin \omega t \quad (2)$$

$$\text{where, } \omega = 2\pi f.$$

The input power P_{dc} and output ac power P_{ac} of the dc/ac inverter are calculated as:

$$P_{dc} = V_{dc} I_{dc} \quad (3)$$

$$P_{ac} = V_m I_m \sin^2 \omega t = \frac{V_m I_m}{2} (1 - \cos 2\omega t). \quad (4)$$

Since $P_{dc} = P_{ac}$, the dc-link current I_{dc} is derived from (3) and (4). Therefore I_{dc} consists of the dc component I_{DC} and the ac component $I_{dc(ac)}$ like (5).

$$I_{dc} = \frac{V_m I_m}{2 V_{DC}} (1 - \cos 2\omega t) = I_{DC} + I_{dc(ac)} \quad (5)$$

$$\text{where, } I_{DC} = \frac{V_m I_m}{2 V_{DC}} \quad I_{dc(ac)} = -\frac{V_m I_m}{2 V_{DC}} \cos 2\omega t$$

Fig. 7. Conventional control scheme of dc/dc boost converter.

Fig. 8. Dc/dc boost converter (rippled dc link).

Thus, the dc-link voltage ripple $V_{dc(ac)}$ can be calculated by integrating the ac component $I_{dc(ac)}$ as (6) and indicating that $V_{dc(ac)}$ contains a 120Hz component with the same phase as the grid voltage V_a .

$$\begin{aligned} V_{dc(ac)} &= \frac{1}{C} \int -I_{dc(ac)} dt = \frac{V_m I_m}{2V_{DC} \cdot C} \frac{1}{\omega} \cdot \sin 2\omega t \\ &= \frac{V_m I_m}{2\omega V_{DC}} \cdot \sin 2\omega t = V_{m(ac)} \sin 2\omega t. \end{aligned} \quad (6)$$

Fig. 4 shows the dc-link voltage. V_{dc} and I_{dc} consist of dc and ac components, which are mainly 2nd-order harmonics, respectively.

B. dc/dc converter control with a ripple free dc-link

Fig. 5 shows a dc/dc boost converter with a ripple free dc-link voltage V_{dc} . This means that I_{dc} does not have a ripple component, either.

PV voltage V_{PV} is represented by the voltage gain of a boost converter as:

$$V_{DC} = \frac{V_{PV}}{1-D}. \quad (7)$$

Thus,

$$V_{PV} = (1-D)V_{DC} = \bar{V}_a \quad (8)$$

where $\bar{V}_a$ is the average value of the voltage across the switch S_b in the steady state and $\bar{V}_a$ is equal to V_{PV} by ignoring the drop voltage in L_1 in the steady state.

Fig. 6 shows duty ratio D generation using the common triangular wave comparison method, where the peak value of the triangular wave is V_{dc} and V_a^* is the command voltage for the dc/dc converter.

Duty cycle D is generated in Fig. 6 as in (9), where V_{dc} becomes V_{DC} because of the ripple free dc-link condition.

$$D = \frac{V_a^*}{V_{DC}}. \quad (9)$$

Therefore, V_{pv} and V_a^* can be calculated as (10) and (11) under the ripple free dc-link condition.

$$V_{PV} = \bar{V}_a = (1-D)V_{DC} = \left(1 - \frac{V_a^*}{V_{DC}}\right) V_{DC} = V_{DC} - V_a \quad (10)$$

$$V_a^* = V_{DC} - \bar{V}_a = V_{DC} - (1-D)V_{DC} = DV_{DC}. \quad (11)$$

Fig. 9. Equivalent circuit of dc/dc converter (rippled dc link).

Fig. 10. (a) AC equivalent circuit (b) DC equivalent circuit.

Fig. 7 shows a conventional control scheme for a dc/dc boost converter, where I_{pv}^* is calculated from the MPPT function and V_a^* is equal to the average voltage across the switch S_b . The transfer function controller is derived such that:

$$\frac{I_{PV}}{I_{pv}^*} = \frac{K_{PV}s + K_{iPV}}{L_{a1}s^2 + K_{PV}s + K_{iPV}}. \quad (12)$$

C. Dc/dc converter control with a rippled dc-link

Fig. 8 shows a dc/dc boost converter with a rippled dc link, where V_{dc} has a dc component V_{DC} and an ac component $V_{dc(ac)}$. In this case, the V_{dc} calculation in (6) is rewritten for convenience as:

$$V_{dc} = V_{DC} + V_{m(ac)} \sin 2\omega t. \quad (13)$$

By combining (8) and (13) for the rippled dc-link:

$$\begin{aligned} \bar{V}_a &= (1-D)V_{dc} = (1-D)(V_{DC} + V_{m(ac)} \sin 2\omega t) \\ &= V_A + V_{a(ac)} \end{aligned} \quad (14)$$

Therefore, the average voltage $\bar{V}_a$ is divided into the dc component V_A and the ac component $V_{a(ac)}$ as shown in Fig. 9.

By applying the superposition principle to the equivalent circuit in Fig. 9, the ac and dc equivalent components are separated as shown in Fig. 10(a) and (b).

The ripple current $I_{L1(ac)}$ through the boost inductor L_1 caused by the 120Hz component of the dc-link current $I_{dc(ac)}$ is derived by solving a differential equation for the ac equivalent circuit in Fig. 10(a):

$$I_{L1(ac)} = \frac{-(1-D)V_{m(ac)}}{2\omega L_1} \sin\left(2\omega t - \frac{\pi}{2}\right). \quad (15)$$

D. Proposed feed-forward ripple current compensation

With the rippled dc link, V_{DC} from (9) is replaced by V_{dc} from (13) and the duty cycle D is derived as:

$$D = \frac{V_a^*}{V_{dc}} \quad (16)$$

$$\text{where, } V_{dc} = V_{DC} + V_{m(ac)} \sin 2\omega t$$

Fig. 11. Proposed dc/dc boost controller with feed-forward compensator.

Fig. 12. Dc/ac inverter with AVR function.

If V_{DC} from (8) is replaced by V_{dc} and D from (9) is replaced by (16) then:

$$\begin{aligned} V_{pv} &= (1 - D)V_{dc} = \left(1 - \frac{V_a^*}{V_{dc}}\right) V_{dc} = V_{dc} - V_a^* \\ &= V_{DC} + V_{m(ac)} \sin 2\omega t - V_a^*. \end{aligned} \quad (17)$$

Since V_{pv} contains a 120Hz component, the 120Hz component can be removed by adding V_{a_ff} term to V_a^* so that:

$$V_a^* = V_{a_fb} + V_{a_ff}, \text{ where } V_{a_ff} = V_{m(ac)} \sin 2\omega t. \quad (18)$$

Then, the V_{pv} from (17) returns to V_{PV} under the ripple free dc link from (10) as:

$$\begin{aligned} V_{pv} &= V_{DC} + V_{m(ac)} \sin 2\omega t - (V_{a_fb} + V_{m(ac)} \sin 2\omega t) \\ &= V_{DC} - V_{a_fb} = V_{PV}. \end{aligned} \quad (19)$$

In other words, the feed-forwarded V_{a_ff} , which is $V_{dc(ac)}$ can remove the propagating 120Hz current ripple through the dc/dc converter. The proposed dc/dc converter controller with the feed-forward compensation is shown in Fig. 11.

E. Dc/ac inverter with AVR

Fig.12 shows a dc/ac inverter control scheme where the automatic voltage regulation (AVR) function is used to restrict the voltage ripple in the dc-link from propagation to the grid current. A pseudo d-q transformation method is adopted in the inverter control for the grid current. The AVR function is defined in (20), where V^* is the command voltage calculated

Fig. 13. (a) Utility voltage V_{AC} (b) Dc-link current I_{dc} (c) Dc-link voltage $V_{dc(ac)}$ at 1.2 kW generation. Fig. 14. (a) PV array current I_{pv} (b) dc-link voltage ripple $V_{dc(ac)}$ without compensation.

from the pseudo d-q transformation method and $V_{DC(ref)} = 380V$ is the reference voltage of the dc-link voltage [4].

$$V^* = \frac{V_{DC(ref)}}{V_{dc}} * V_s^* = \frac{(V_{DC(ref)} * V_s^*)}{(V_{DC(ref)} + V_{dc(ac)})} \quad (20)$$

$$\text{where, } V_{dc(ac)} = V_{m(ac)} \sin(2\omega t). \quad (21)$$

III. SIMULATION FOR AC RIPPLE MITIGATION

Current control using a pseudo d-q transformation with AVR is simulated by PSIM. 1.2kW of power is generated and a 120Hz ripple is generated in the dc-link voltage, current and boost inductor current. Fig. 13 shows the grid voltage V_{ac} , the dc-link current I_{dc} and the dc-link voltage ripples $V_{dc(ac)}$. The simulated waveforms are well matched with waveforms calculated from the derived equations. Fig. 14 shows the PV array current I_{pv} and the dc-link voltage ripple $V_{dc(ac)}$ without a compensator with gain $k_p=6$, $\tau=3ms$, where the I_{pv} contains 3.7A of peak-to-peak 120Hz ripple current. Fig. 15 shows the same waveforms with the proposed feed-forward compensator and the same gains. It shows that the current ripples are reduced. Therefore, the effectiveness of ripple reduction with the proposed compensator is verified.

IV. EXPERIMENTAL RESULTS

A prototype of the 3kW PV PCS shown in Fig. 16 was built in order to compare the ripple reduction with and without compensation. The 3kW PV PCS is implemented fully in the

Fig. 15. (a) PV array current with the feed-forward compensation I_{pv} (b) dc-link voltage ripple $V_{dc(ac)}$.

Fig. 16. Prototype of the 3kW PV PCS.

software adopted for a TMS320F2812 digital signal processor. The switching times of each converter are implemented fully in the software, and the voltage and current signals are measured using an internal 12-bit-resolution analog-to-digital converter in the DSP. A digital-to-analog converter is used to display all of the waveforms. The switching frequency of the inverter is 10kHz and the dead-time is $3\mu\text{sec}$. Therefore, the output command PWM compensates for the dead time effect.

Fig. 17 shows the PV array current I_{pv} . It includes 4A of peak-to-peak ripple with the switching ripple, where the ripple factor is 52.63% and the dc-link voltage contains 6V of peak-to-peak ripple $V_{dc(ac)}$ without compensation (gain $k_p=6$, $\tau=3\text{ms}$). Therefore the CMPPT cannot achieve high efficiency.

Fig.18 shows the same waveforms with the proposed feed-forward compensation. It illustrates a significant reduction in ripples, even with the same gains (gain $k_p=6$, $\tau=3\text{ms}$). I_{pv} includes a ripple current with 3A of peak-to-peak ripple, where the ripple factor is 39.5% and V_{dc} includes the same peak-to-peak ripple $V_{dc(ac)}$. Therefore, the proposed feed-forward ripple current compensation method significantly reduces the ac ripples in the dc/dc converter. It demonstrates a 41.8% decrease in ripple.

Finally, when generating 3kW of power, the PV array current I_{pv} demonstrated a significant reduction of ripples as shown in Fig. 19. It also shows a peak-to-peak ripple $V_{dc(ac)}$ that is just 0.2A and this means that the CMPPT can reach the MPP easily. Hence, the PV PCS efficiency can be increased by reducing the perturbation ripples in the MPP. Fig. 20 shows the grid current I_{grid} using the AVR function in the dc/ac

Fig. 17. (a) Current ripple with higher gains I_{pv} [2A/div] (b) Dc-link voltage ripples $V_{dc(ac)}$ [2.5V/div].

Fig. 18. (a) Current ripple with compensation I_{pv} [2A/div] (b) Dc-link voltage ripples $V_{dc(ac)}$ [2.5V/div].

inverter control and it verifies that the dc-link ripple has no effect on the grid current waveform.

V. CONCLUSIONS

A PV PCS that contains single-phase dc/ac inverters tends to draw an ac ripple current at twice the output frequency. Such a ripple current perturbs the operating points of the solar cells continuously and it may reduce current based maximum power point tracking (CMPPT) efficiency. In this paper, the ripple current generation in the dc-link and boost inductor has been analyzed using an ac equivalent circuit of the dc/dc boost

Fig. 19. Array current ripples 3kW generation I_{pv} [0.05A/div].

Fig. 20. Grid current control with AVR at 3kW generation (a) Grid voltage V_{grid} [50V/div] (b) Grid current I_{grid} [2.5A/div].

converter. A new feed-forward ripple current compensation method has been proposed to incorporate a current control loop into the dc/dc converter control for ripple reduction. The proposed method has been verified in both simulation and experiments. It shows a 41.8 % reduction in peak-to-peak ac ripple. In addition, the dc/ac inverter has includes the AVR function to mitigate the effect of the ac ripple voltage on the grid current. A 3kW PV PCS has been built and its experimental results verify the effectiveness of the proposed method.

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advanced converters and control for renewable energy systems and micro-grids.

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