Reduction of Output Voltage Ripples in Single-Phase PWM Rectifier with Active Power Decoupling Circuit

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***Abstract*-- In this paper, a low-cost single-phase PWM rectifier with small DC-link capacitors is proposed, where a buck-boost converter with a low power rating is added at the DC link. By controlling the auxiliary circuit so as to absorb the voltage ripple in the DC link, the second-order voltage ripple in DC-link capacitor can be reduced significantly. Therefore, a small film capacitor can be utilized to replace the bulky electrolytic capacitors. The simulation results are shown to verify the validity of the proposed method.**

***Index Terms*--Active power decoupling, single-phase rectifier, voltage ripple**

1. Introduction

Nowadays, single-phase AC/DC PWM converters have been widely used in residential applications. The simplest circuit of an AC/DC converter topology is a full-bridge diode rectifier with a relatively low cost. However, there are several drawbacks of this circuit such as high-ripple components of the source current and poor power factor. To improve the power quality issues for this circuit, a power factor correction circuit is inserted between the rectifier and filter capacitor. With this circuit, the source current can be controlled to be sinusoidal with a unity power factor. However, when the DC chopper is added, the switching frequency should be raised to reduce the voltage ripple and lessen the converter size. This makes the increased loss and reduced reliability of the converter. To overcome this difficulty, a new topology has been introduced, in which a PWM rectifier with two switches and two diodes is adopted [1]. This converter gives good performances such as sinusoidal control of source current, unity power factor, simple power circuit, and high efficiency [2].

In single-phase PWM rectifier, there is a common problem of second-order ripple power in the DC link. It generates a ripple in the DC-link voltage at twice the line frequency, which is harmful to the converter. To absorb this low-frequency ripple, bulky electrolytic capacitors are usually used. This, however, results in a large converter size, consequently, low power density. Therefore, it is desirable to replace the bulky electrolytic capacitors by reliable film capacitors if possible while keeping a low ripple in the DC-link voltage. There have been some research results about a reduction of DC-link capacitors in single-phase converters. The first approach is based on injecting a harmonic current, in which the third-harmonic current is injected into the source side to suppress the power fluctuation in the DC link [3]. However, the main drawback of this method is a high THD of the input current. Another method is to add an active energy circuit in parallel with the DC-link to divert the ripple energy from the DC-link capacitor to the auxiliary circuit. In [4], an auxiliary circuit including one capacitor, one inductor and two switches is added to bypass the energy ripple from the DC-link. However, the remaining voltage ripple is still relatively high although considerably reduced.

In this paper, a low-cost single-phase rectifier with small DC-link capacitor is proposed, in which a bidirectional buck-boost converter with small capacitor as an auxiliary circuit is used to reduce the ripple energy flow into the DC-link. As a result, the DC-link capacitor is reduced eight times compared with the conventional topology. Therefore, it is possible to use highly reliable film capacitors instead of using bulky electrolytic capacitors. The validity of the proposed method is shown by simulation results, where the ripple of the DC-link voltage is about 2.4%.

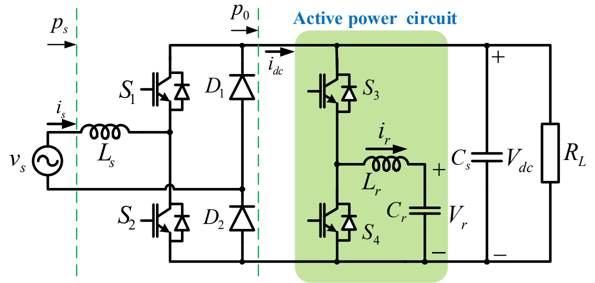

Fig. 1. Single-phase rectifier with proposed active power circuit.

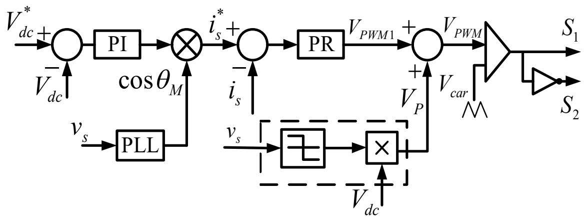

Fig. 2. Control block diagram for single-phase rectifier.

2. Circuit Configuration

i) Control of single-phase rectifier

Fig. 1 shows a single-phase PWM converter, in which the power circuit consists of two IGBTs and two diodes. This converter offers benefits such as almost sinusoidal input current, unity power factor control in the source side, simple power circuit compared with single-phase power factor correction converter. There are four operation modes in this single-phase PWM converter, which depends on the polarity of the voltage source.

Fig. 2 shows the control block diagram of single-phase rectifier. The proportional-resonant (PR) controller is adopted to control the source current. For controlling the DC-link voltage, the proportional-integral (PI) controller is used. In order to make the input current sinusoidal, the polarity of the source voltage is detected and multiplied by the DC-link voltage [2]. Then, this compensation, V_P, is added to the output of the PR controller.

ii) Analysis of single-phase power ripples

The power flow in the single-phase rectifier is shown in Fig. 1. It is assumed that the input voltage and current are sinusoidal and in phase as $v_s = \sqrt{2}V_s \sin(\omega t)$ and $i_s = \sqrt{2}I_s \sin(\omega t)$, respectively. Then the instantaneous input power is

$$p_s = \sqrt{2}V_s \sin(\omega t) \times \sqrt{2}I_s \sin(\omega t) = V_s I_s (1 - \cos(2\omega t)) \quad (1)$$

where V_s and I_s are the rms values of the input voltage and current, respectively, and ω is the line angular frequency.

The power of the input inductor can be obtained

$$p_{Ls} = i_s \times L_s \frac{di_s}{dt} = \omega L_s I_s^2 \sin(2\omega t). \quad (2)$$

Neglecting the power losses of the devices, the output power of the rectifier is expressed

$$p_0 = p_s - p_{Ls} = V_s I_s - I_s\sqrt{V_s^2 + \omega^2 L_s^2 I_s^2}\sin(2\omega t + \varphi) \quad (3)$$

where $\varphi = \arctan\left(\dfrac{V_s}{\omega L_s I_s}\right)$. The power flow into the DC link consists of two parts, which are a constant power and a ripple

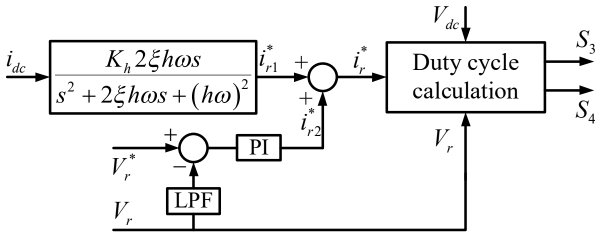

Fig. 3. Control block diagram of auxiliary circuit.

Table I. Parameters of single-phase rectifier

Parameters	Value
Voltage source (peak), AC frequency	220 V, 60 Hz
L_s, C_s	3 mH, 250 µF
DC-link voltage	340 V
Output power	2 kW
Lr, Cr	50 µH, 200 µF
Switching frequency	10 kHz

power defined as, respectively

$$p_0 = V_s I_s$$
$$p_r = -I_s\sqrt{V_s^2+\omega^2 L_s^2 I_s^2}\sin(2\omega t+\varphi). \tag{4}$$

iii) Control of active decoupling circuit

In order to reduce the voltage ripple in the DC-link capacitor, the power ripple should be consumed by auxiliary capacitor. Therefore, the current in auxiliary circuit should be controlled to track the ripple current i_r. Hence, the compensation ripple current i_r should be

$$i_r = \frac{p_r}{V_{dc}} = -\frac{I_s\sqrt{V_s^2+\omega^2 L_s^2 I_s^2}\sin(2\omega t+\varphi)}{V_{dc}}. \tag{5}$$

However, it is difficult to obtain the current reference in (5). So, the current ripple reference is extracted from the DC current, i_{dc}, through the resonant compensator [5]

$$K_R(s) = \frac{K_h 2\xi h\omega s}{s^2+2\xi h\omega s+(h\omega)^2} \tag{6}$$

where $K_h = 2, \xi = 0.01, h = 2, \omega = 2\pi f$.

Fig. 3 shows the control block diagram of auxiliary circuit. To prevent overcharging of the auxiliary capacitor, a voltage control loop is adopted to control the average value of capacitor voltage. The duty cycles for charging and discharging states are shown in (7), and (8), respectively [4]

$$D_1 = \sqrt{\frac{2i_r^* L_r}{T_s(V_{dc}-V_r)}} \tag{7}$$

$$D_2 = \sqrt{\frac{2i_r^* L_r (V_{dc}-V_r)}{T_s V_r^2}} \tag{8}$$

where D_1, D_2 is duty cycle for charging state and discharging state, respectively. V_r, V_{dc} is auxiliary capacitor voltage and DC-link voltage, respectively.

3. Simulation Results

The simulation parameters are summarized in Table I. The auxiliary capacitor and inductor are selected to be 200 µF and 50 µH, respectively [4]. Fig. 4 shows the test results for a 2-kW single-phase PWM rectifier without using auxiliary circuit and with adding auxiliary circuit, respectively. It can be seen from Fig. 4(a) that the DC-link voltage ripple is about 27% due to the small DC-link capacitor. However, by adding the auxiliary circuit, the DC-link voltage ripple is reduced to 2.4%, even with a 250µF DC-link capacitor as shown in Fig. 4(b).

The comparison between the conventional method and the active ripple energy storage method is shown in Fig. 5. For the conventional electrolytic capacitors, a 2 mF DC-link capacitor

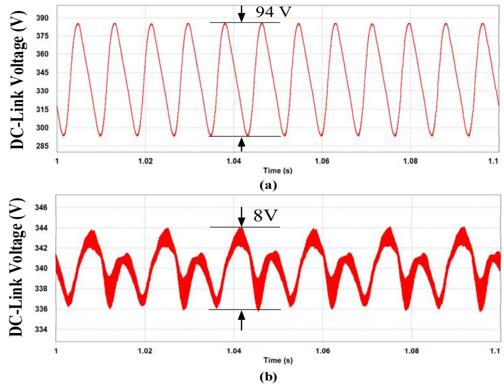

Fig. 4. DC-link voltage. a) Without using auxiliary circuit. b) With using auxiliary circuit.

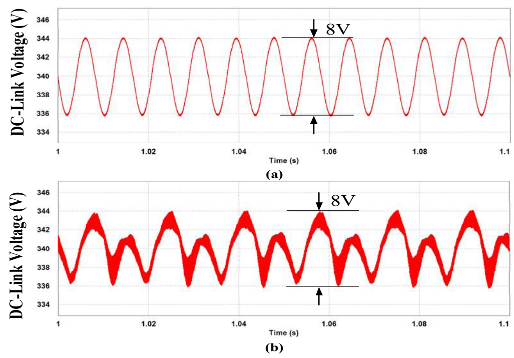

Fig. 5. DC-link voltage. a) Using auxiliary circuit with 250 uF of DC-link capacitor. b) Conventional electrolytic capacitor with 2 mF.

was needed to meet the same DC-link voltage ripple with the proposed active ripple energy storage method.

4. Conclusions

This paper has presented a low-cost single-phase PWM rectifier circuit, in which an active ripple power decoupling circuit is adopted to reduce the ripple in DC-link voltage. With this circuit, the required DC-link capacitance can be reduced significantly so that it is possible to utilize the highly reliable film capacitors instead of bulky electrolytic capacitors. The simulation results have been shown to verify the effectiveness of the proposed method.

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