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Bi-directional single-phase half-bridge rectifier for power quality compensation

B.R. Lin, T.L. Hung and C.H. Huang

Abstract: A single-phase half-bridge rectifier with a capacitor clamped scheme is proposed. Four power switches and one flying capacitor are employed in the proposed rectifier. Bipolar and unipolar PWM control schemes are used to perform power factor correction and achieve low total harmonic distortion of line current. A neutral point voltage balance compensator, hysteresis current controller and DC link voltage regulator are used to balance neutral point voltage, to track line current command, and to maintain the constant DC bus voltage. The proposed control scheme and the circuit configuration can also perform a shunt active power filter operation to eliminate the harmonic currents and compensate the reactive power generated from the nonlinear load. Analytical and experimental results are presented to illustrate the validity and effectiveness of the proposed control scheme.

1 Introduction

Power pollution generated by nonlinear loads such as diode and thyristor rectifiers deteriorates the quality of power in the transmission or distribution system. Passive filters with fixed compensation characteristics are ineffective in filtering the current harmonics. Active power factor correctors [1–6] and active filters [7–10] have been successfully researched and developed for power factor correction and current harmonics elimination, respectively. A power factor corrector is used as a front-end stage of AC/DC/AC or AC/DC converters to supply a controllable DC bus voltage. The input current of the converter is controlled to be a clean sine wave in phase with the mains voltage. For unidirectional power flow applications, a diode rectifier followed by a DC/DC converter [1–3] is employed to achieve unity power factor. If the rectifier is used in the front stage of the motor drive, a PWM rectifier with bi-directional power flow capability [4–6] is generally needed to send the regenerating power to the AC mains instead of the DC braking resistor. A single-phase full-bridge switching mode rectifier is controlled to generate a bipolar or unipolar PWM voltage waveform on the AC side. The voltage stress of the power switches equals the DC-link voltage. For a half-bridge switching mode rectifier, a bipolar PWM voltage waveform is generated on the AC terminal. A single-phase half-bridge PWM rectifier employs two power switches to achieve double boost conversion in the DC bus. The voltage stress of the power switches is equal to the DC bus voltage. For medium DC-link applications, the voltage stress of the switches is very high and the power semiconductors are very expensive.

Developments and applications of active filters have been researched because of increasing concern with the power quality at the consumer or distribution side. Shunt active power filters with voltage source inverters are connected in parallel with the mains to operate as a current source to eliminate the harmonic and reactive currents generated by the nonlinear load. Quick computation of the compensated component is generally required for the purpose of reactive power compensation and harmonic current suppression. Several control algorithms [7–10] such as instantaneous reactive power theory, sliding mode control, predictive scheme, state feedback scheme and synchronous reference frame have been proposed. If the PWM rectifier can perform both functions of power factor corrector and active power filter [11–13], the cost of the system can be reduced.

Multilevel converters [14–17] are proposed to reduce the voltage stress of power semiconductors, and reduce the voltage harmonics and electromagnetic interference. A new bi-directional single-phase half-bridge rectifier based on the neutral-point capacitor-clamped scheme is proposed to draw a nearly unity power factor and regulate the DC-link voltage. A unipolar PWM voltage waveform is generated on the AC side of the rectifier based on the high-bandwidth hysteresis current control scheme. A low-bandwidth voltage controller is used to maintain the DC-link voltage at the desired value. By using the same control scheme, the proposed rectifier can be worked as a switching mode rectifier to supply the DC side power and worked as a shunt active filter to suppress the harmonics and compensate the reactive power generated by the nonlinear load. The proposed power quality compensation can reduce the hardware cost of the shunt active filter needed in the conventional shunt active filter approach. Based on the proposed control scheme, the line current is controlled to track the reference current commands with high power factor and low current harmonics. Finally, the performance of the proposed control scheme is evaluated by experimental results obtained from a laboratory prototype.

2 System description

The proposed single-phase rectifier is based on a half-bridge circuit configuration with one clamped capacitor as shown in Fig. 1*a* to reduce the voltage harmonic content on the

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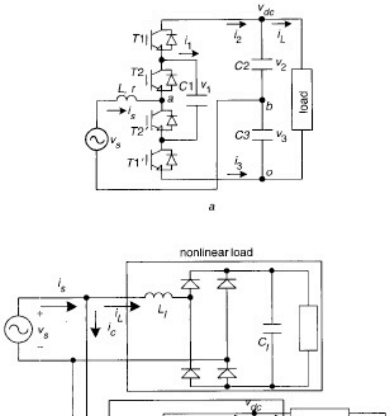


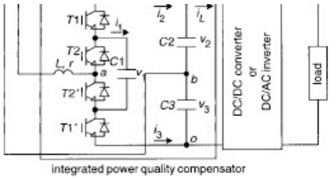
3 Switching mode rectifier

3.1 Operation principle

Before analysis of the proposed rectifier, all power switches and diodes are considered ideal. To avoid power switches conducting at the same time, the constraints on power switches in the proposed rectifier are defined as

$$Ti + Ti' = 1,\ i = 1, 2 \tag{1}$$

where $Ti = 1$ (or 0) if switch Ti is turned on (or off). Thus, there are only two independent power switches $T1$ and $T2$ in the proposed rectifier. According to the switching states of these two power switches, there are four valid switching states as shown in Table 1. If the capacitor voltages are controlled to be balanced, three voltage levels $v_{dc}/2$, 0 and $-v_{dc}/2$ are generated on the AC terminal. There are two operation states to generate voltage $v_{ab} = 0$. Based on the voltage level on the AC terminal v_{ab}, the operation of the proposed rectifier can be classified into three operation modes as shown in Fig. 2. In the first operation mode as shown in Fig. 2*a*, power switches $T1$ and $T2$ are turned on to generate voltage $v_{ab} = v_{dc}/2$ (assuming $v_1 = v_2 = v_3 = v_{dc}/2$). The line current is decreasing because $v_L = Ldi_s/$



b

Fig. 1 *Proposed half-bridge rectifier*
a For power factor correction
b For power quality compensator

AC terminal of the rectifier. The circuit configuration of the proposed rectifier includes four power switches, one clamped capacitor, one boost inductor and two DC side capacitors. The voltage stress of the four power switches *T*1, *T*2, *T*1′ and *T*2′ is $v_{dc}/2$. The control goals of the proposed rectifier are performing power factor correction, balancing neutral point voltage and maintaining constant DC bus voltage. A hysteresis current control in the inner high-bandwidth control scheme is employed to track the line current command in phase with the mains. A proportional integral voltage control in the outer low-bandwidth control scheme is used to regulate the DC bus voltage. A neutral point voltage compensator is used to balance capacitor voltages, $v_1 = v_2 = v_3 = v_{dc}/2$. By the appropriate control algorithm, a bipolar (or unipolar) PWM voltage waveform is generated on the AC terminal. Under the same control algorithm, the proposed rectifier can also be worked as a power quality compensator to suppress current harmonics and compensate the reactive power when a nonlinear load is connected to the system as shown in Fig. 1*b*. At the same time, the adopted rectifier also provides the necessary active power to the output load. The nonlinear load consists of the diode rectifier followed by a capacitor. To maintain a constant DC bus voltage, a PI voltage controller is employed to obtain line current command. Only line current is sensed in the current control loop to track the line current command.

$dt = v_s - v_{dc}/2 < 0$. The positive (or negative) line current is charging the capacitor *C*2. There are two operation states in the second operation mode to generate voltage $v_{ab} = 0$. If the power switches *T*1 and *T*2′ are turned on as shown in Fig. 2*b*, the positive (or negative) line current is charging capacitor *C*2 (or *C*1) and discharging capacitor *C*1 (or *C*2). If the power devices *T*1′ and *T*2 are turned on as shown in Fig. 2*c*, the capacitor *C*1 (or *C*3) is charged and capacitor *C*3 (or *C*1) is discharged by the positive (or negative) line current. In this operation mode, the mains current is increasing (or decreasing) if the mains is positive (or negative). These two operation states can be used to balance the capacitor voltage v_1. In the third operation mode, power switches *T*1′ and *T*2′ are turned on, as shown in Fig. 2*d*, to generate AC terminal voltage $v_{ab} = -v_{dc}/2$. The line current is increasing in this operation mode because the boost inductor voltage $v_L = v_s + v_{dc}/2 > 0$. The negative (or positive) line current will charge (or discharge) capacitor *C*3. Based on the proper selection of the operation states, three voltage levels, $v_{dc}/2$, 0 and $-v_{dc}/2$, are generated on the AC side of the rectifier.

Table 1: Valid switching states of the proposed rectifier

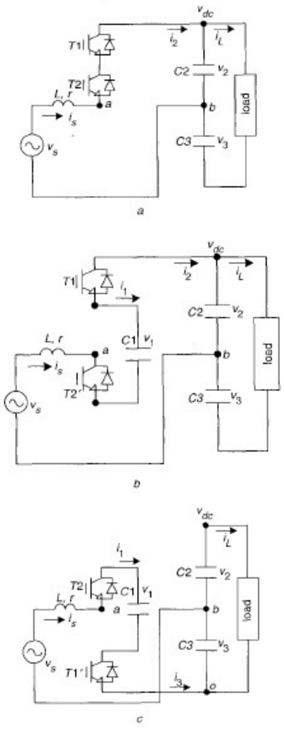
Valid switching states	*T*1	*T*2	v_{ab}	v_{ab} ($v_1 = v_2 = v_3 = v_{dc}/2$)	Mode
1	1	1	v_2	$v_{dc}/2$	1
2	1	0	$-v_1+v_2$	0	2
3	0	1	v_1-v_3	0	2
4	0	0	$-v_3$	$-v_{dc}/2$	3

3.2 System analysis

Based on the four possible operation states of the proposed rectifier, the differential equations on the AC and DC side of the rectifier can be given as follows:

$$\frac{di_s}{dt} = \frac{v_s}{L} - \frac{r}{L} i_s - \frac{T2 - T1}{L} v_1 - \frac{T1}{L} v_2 - \frac{T1 - 1}{L} v_3 \qquad (2)$$

$$\frac{dv_1}{dt} = \frac{T2 - T1}{C1} i_s \qquad (3)$$



a

b

c

The dynamic equation of the proposed rectifier is given as

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{a}(\boldsymbol{x}) + \boldsymbol{b}_1(\boldsymbol{x})u1 + \boldsymbol{b}_2(\boldsymbol{x})u2 + \boldsymbol{b}_3(\boldsymbol{x})u3 \\ &= \boldsymbol{a}(\boldsymbol{x}) + \begin{bmatrix} \boldsymbol{b}_1(\boldsymbol{x}) & \boldsymbol{b}_2(\boldsymbol{x}) & \boldsymbol{b}_3(\boldsymbol{x}) \end{bmatrix} \begin{bmatrix} u1 \\ u2 \\ u3 \end{bmatrix} \\ &= \boldsymbol{a}(\boldsymbol{x}) + \boldsymbol{B}(\boldsymbol{x})\boldsymbol{u} \end{aligned} \qquad (6)$$

$$\boldsymbol{y} = \boldsymbol{c}(\boldsymbol{x}) \qquad (7)$$

where

$$\boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} i_s \\ v_1 \\ v_2 \\ v_3 \end{bmatrix}, \boldsymbol{u} = \begin{bmatrix} u1 \\ u2 \\ u3 \end{bmatrix} = \begin{bmatrix} T2 - T1 \\ T1 \\ T1 - 1 \end{bmatrix},$$

$$\boldsymbol{c}(\boldsymbol{x}) = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} = \begin{bmatrix} i_s \\ v_1 - v_2 \\ v_1 - v_3 \\ v_2 + v_3 \end{bmatrix},$$

$$\boldsymbol{a}(\boldsymbol{x}) = \begin{bmatrix} \frac{v_s - ri_s}{L} \\ 0 \\ -\frac{v_2+v_3}{RC2} \\ -\frac{v_2+v_3}{RC3} \end{bmatrix}, \boldsymbol{B}(\boldsymbol{x}) = \begin{bmatrix} \boldsymbol{b}_1(\boldsymbol{x}) & \boldsymbol{b}_2(\boldsymbol{x}) & \boldsymbol{b}_3(\boldsymbol{x}) \end{bmatrix}$$
$$= \begin{bmatrix} -\frac{v_1}{L} & -\frac{v_2}{L} & -\frac{v_3}{L} \\ \frac{i_s}{C1} & 0 & 0 \\ 0 & \frac{i_s}{C2} & 0 \\ 0 & 0 & \frac{i_s}{C3} \end{bmatrix} \qquad (8)$$

The controllability matrix $\boldsymbol{P}(\boldsymbol{x})$ [18] of the system (6) and the observability matrix $\boldsymbol{Q}(\boldsymbol{x})$ [19] of the system (7) are given as

$$\boldsymbol{P}(\boldsymbol{x}) = [\boldsymbol{b}_1(\boldsymbol{x}), \quad \boldsymbol{b}_2(\boldsymbol{x}), \quad \boldsymbol{b}_3(\boldsymbol{x}), \quad [\boldsymbol{a}(\boldsymbol{x}), \quad \boldsymbol{b}_1(\boldsymbol{x})] \quad [\boldsymbol{a}(\boldsymbol{x}), \quad \boldsymbol{b}_2(\boldsymbol{x})] \quad [\boldsymbol{a}(\boldsymbol{x}), \quad \boldsymbol{b}_3(\boldsymbol{x})]]$$

$$\left[-\frac{v_1}{L} \quad -\frac{v_2}{L} \quad -\frac{v_3}{L} \quad -\frac{rv_1}{L^2} \qquad -\frac{rv_2}{L^2} \qquad -\frac{rv_3}{L^2} \right.$$

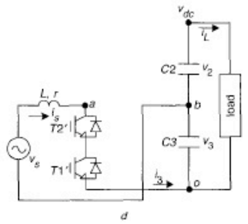


Fig. 2 *Operation modes of the proposed rectifier*
a Mode 1 (switching state 1)
b Mode 2 (switching state 2)
c Mode 2 (switching state 3)
d Mode 3 (switching state 4)

$$\frac{dv_2}{dt} = \frac{T1}{C2} i_s - \frac{v_2 + v_3}{RC2} \tag{4}$$

$$\frac{dv_3}{dt} = \frac{T1 - 1}{C3} i_s - \frac{v_2 + v_3}{RC3} \tag{5}$$

$$= \begin{bmatrix} \frac{i_s}{C1} & 0 & 0 & \frac{v_s - ri_s}{LC1} & 0 & 0 \\ 0 & \frac{i_s}{C2} & 0 & 0 & \frac{v_s RC2 - rRC2i_s + Li_s}{RL(C2)^2} & \frac{i_s}{RC2C3} \\ 0 & 0 & \frac{i_s}{C3} & 0 & \frac{i_s}{RC2C3} & \frac{v_s RC3 - rRC3i_s + Li_s}{RL(C3)^2} \end{bmatrix} \tag{9}$$

$$\boldsymbol{Q}(\boldsymbol{x}) = \begin{bmatrix} dc_1 \\ dc_2 \\ dc_3 \\ dc_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & 1 \end{bmatrix} \tag{10}$$

where

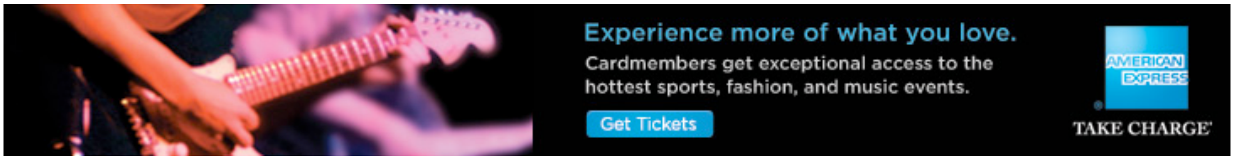
$$[\boldsymbol{a}(\boldsymbol{x}), \boldsymbol{b}_i(\boldsymbol{x})] = \frac{\partial \boldsymbol{b}_i(\boldsymbol{x})}{\partial \boldsymbol{x}} \boldsymbol{a}(\boldsymbol{x}) - \frac{\partial \boldsymbol{a}(\boldsymbol{x})}{\partial \boldsymbol{x}} \boldsymbol{b}_i(\boldsymbol{x}) \tag{11}$$

$$dc_i = \left[\frac{\partial c_i}{\partial x_1}, \ \frac{\partial c_i}{\partial x_2}, \ \frac{\partial c_i}{\partial x_3}, \ \frac{\partial c_i}{\partial x_4} \right], \ i = 1, 2, 3, 4 \tag{12}$$

The rank $(\boldsymbol{P}(\boldsymbol{x})) = 4$ and rank $(\boldsymbol{Q}(\boldsymbol{x})) = 4$, and hence the proposed rectifier is controllable and observable.

3.3 Control scheme

Two PWM control schemes (bipolar and unipolar PWM) are proposed to improve the input power factor of the proposed rectifier. A sinusoidal line current with nearly unity power factor is drawn and the DC bus voltage is controlled to be constant. Fig. 3*a* gives the simplified



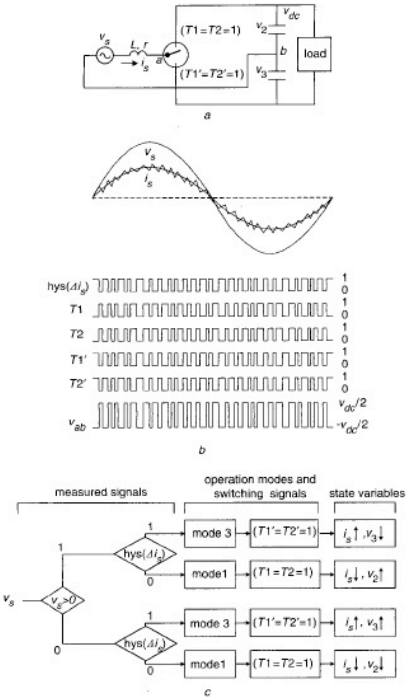


Fig. 3 *Bipolar PWM operation of the proposed rectifier*
a Simplified equivalent circuit
b Bipolar PWM waveform

$$T1' = T2' = \text{hys}(\Delta i_s) \tag{14}$$

where $\Delta i_s = i^*_s - i_s$ and

$$\text{hys}(\Delta i_s) = \begin{cases} 1, \ \Delta i_s > h \\ 0, \ \Delta i_s < -h \end{cases} \tag{15}$$

For the unipolar PWM operation, three voltage levels ($v_{dc}/2$, 0 and $-v_{dc}/2$) are generated on the AC side of the rectifier. Four operation states of the proposed rectifier are all used in this PWM operation. Fig. 4*a* gives the simplified equivalent circuit of the rectifier. For positive mains voltage, the operation mode 1 ($T1 = T2 = 1$) and operation mode 2 ($T1 = T2' = 1$ or $T1' = T2 = 1$) are used to generate the voltage $v_{ab} = v_{dc}/2$ and 0 respectively. Operation mode 1 is adopted to decrease the line current. Operation mode 2 is used to increase the line current. Two operation states are selected to charge or discharge capacitor $C1$. Power switches $T1'$ and $T2$ are turned on to charge capacitor $C1$ and power switches $T1$ and $T2'$ are turned on to discharge capacitor $C1$. Therefore these two switching states are used to control the capacitor voltage v_1. For negative mains voltage, operation modes 2 and 3 are selected to achieve $v_{ab} = 0$ and $-v_{dc}/2$. The switching states 2 and 3 shown in Table 1 are used to decrease the line current. Capacitor $C1$ is charged (or discharged) in switching state 2 (or state 3). Operation mode 3 is selected to increase the line current. Therefore, three voltage levels are achieved on the AC terminal of the proposed rectifier. Fig. 4*b* gives the PWM waveform of power switches and the AC side voltage v_{ab}. Fig. 4*c* gives the control strategy of the unipolar PWM operation. First, the sign of the mains voltage is detected. If the mains voltage is positive and the hysteresis current comparator is negative, operation mode 1 is selected to decrease the line current and to generate voltage $v_{ab} = v_{dc}/2$. If $v_s > 0$, hys$(\Delta i_s) = 1$ and $v_1 > v_{dc}/2$, then switching state 2 ($T1 = T2' = 1$) is selected to increase the line current and decrease the capacitor voltage v_1. On the other hand if $v_s > 0$, hys$(\Delta i_s) = 1$ and $v_1 < v_{dc}/2$, then switching state 3 ($T1' = T2 = 1$) is selected to increase the line current and increase the

b Bipolar PWM waveform
c Control strategy

equivalent circuit of the proposed rectifier for the bipolar PWM operation. Only operation mode 1 ($T1 = T2 = 1$) and mode 3 ($T1' = T2' = 1$) are used in the control scheme. The switching signals of power switches and AC terminal voltage of the rectifier are shown in Fig. 3*b*. The AC side voltage v_{ab} is equal to $v_{dc}/2$ or $-v_{dc}/2$. The switching signals of $T1$ and $T2$ are related to the line current error between the line current command and the measured line current. Hysteresis current control in the high-bandwidth control scheme is used to track the mains current command. When the line current error reaches the upper hysteresis band, power switches $T1'$ and $T2'$ are turned on (operation mode 3) to generate AC side voltage $v_{ab} = -v_{dc}/2$ and to increase the line current. If the line current error falls below the lower hysteresis band, power switches $T1$ and $T2$ are turned on (operation mode 1) to generate AC side voltage $v_{ab} = v_{dc}/2$ and to decrease the line current. The bipolar PWM control strategy of the proposed rectifier is given in Fig. 3*c*. Based on the hysteresis current control, the corresponding switching signals of power switches are given as

$$T1 = T2 = 1 - \mathrm{hys}(\Delta i_s) \tag{13}$$

capacitor voltage v_1. In the same way, switching states 2, 3 and 4 are used for negative mains voltage. Based on the proposed control strategy, the switching signals of power devices can be expressed as

$$\begin{aligned} T1 =& \mathrm{sign}(v_s) \cdot \mathrm{comp}(v_1 - v_{dc}/2) \\ &+ [1 - \mathrm{hys}(\Delta i_s)] \cdot [1 - \mathrm{comp}(v_1 - v_{dc}/2)] \end{aligned} \tag{16}$$

$$\begin{aligned} T2 =& \mathrm{sign}(v_s) \cdot [1 - \mathrm{comp}(v_1 - v_{dc}/2)] \\ &+ [1 - \mathrm{hys}(\Delta i_s)] \cdot \mathrm{comp}(v_1 - v_{dc}/2) \end{aligned} \tag{17}$$

The control block of the proposed rectifier is given in Fig. 5. A proportional-integral voltage control in the outer low-bandwidth control scheme is employed to maintain a constant DC bus voltage. A phase-locked loop circuit is adopted to generate a unit sinusoidal wave in phase with the mains voltage. A neutral point voltage compensator is added to the line current command to balance the neutral point voltage. The sensed line current is compared with the reference line current. Hysteresis current control in the high-bandwidth control scheme is used to track the line current command. A line voltage comparator is used to detect the sign of the mains voltage. Based on (13)–(14) or (16)–(17), the appropriate switching signals of

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