Steady State and Transient Analysis of A Three Phase Current-Fed Z-Source PWM Rectifier

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Abstract- The voltage-source PWM rectifier (VSR) is a boost converter, thus its dc output voltage is much greater than the ac voltage, whereas the current-source PWM rectifier (CSR) is a buck converter and having a dc voltage smaller than its ac voltage. In addition, the CSR can only provide unidirectional power flow, thus unsuitable for regenerative operation. Recently, reverse blocking IGBT (RB-IGBT) has been developed for current-source and matrix converters. In this paper, a current-fed Z-source PWM rectifier is proposed to overcome the limitations of the traditional VSR and CSR. The current-fed Z-source PWM rectifier with only six active switches can buck and boost voltage and provide bidirectional power flow. This paper describes the operating principle of this current-fed Z-source PWM rectifier, presents a detailed steady state analysis and transient analysis. A RB-IGBT based current-fed Z-source PWM rectifier has been developed in laboratory. Both simulation and experimental results are shown to verify the operation and theoretical analysis.

Keywords-component; current-fed; Z-source; rectifier; SVPWM; steady state; transient

I. INTRODUCTION

The conventional Voltage Source Rectifier (VSR) and Current Source Rectifier (CSR) both have following limitations: they are either a boost or a buck rectifier; they are vulnerable to EMI noise in reliability; The Z-source rectifier is proposed to overcome these drawbacks. CSR has competitive perspective because it can achieve bidirectional power flow without replacing the diode with a bidirectional conducting, unidirectional blocking switch like VSR. The newly developed reverse blocking IGBT (RB-IGBT) promotes the research about current-fed Z-source PWM rectifier. Its configuration is shown in Fig. 1. This paper presents its operating principle, control strategy, circuit steady-state and dynamic features. Simulations and a RB-IGBT based prototype are given to verify the theoretical analysis.

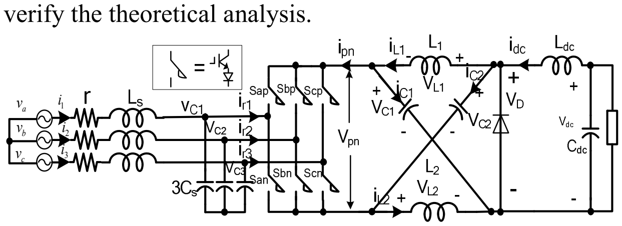


Fig.1. Current-fed Z-source PWM rectifier

II. CONVENTIONAL CURRENT SOURCE PWM RECTIFIER

A. *Conventional CSR SVPWM control method*

The space vector control strategy is applied here to control the conventional CSR which is described explicitly in [4].Unlike the VSR, CSR has 9 switching states. It has 6 active states and three short zero states when both of the upper and lower switches in phase leg A or B or C short together. For output current synthesis, in one sampling interval T, the output current vector $\vec{I}$ is commonly split into the two nearest adjacent current vectors ($\vec{I}_i$ and $\vec{I}_{i+1}$, i=1,…6) and one of three short zero vectors($\vec{I}_7, \vec{I}_8, or\ \vec{I}_9$). So $\vec{I}$ can be synthesized as:

$$\vec{I}T_s = I_i T_i + I_{i+1} T_{i+1} + I_0 T_0 \tag{1}$$

where T_i, T_{i+1}, T_0 are time for the adjacent vectors I_i, I_{i+1}, I_0 respectively. Assume m is equivalent modulation which has maximum value 1.15 and θ is the angle of the current reference vector. So the three time period for different space vector is calculated as:

$$\begin{aligned} T_i &= \frac{\sqrt{3}}{2} m \sin(\frac{\pi}{6} - \theta) \cdot T_s \\ T_{i+1} &= \frac{\sqrt{3}}{2} m \sin(\frac{\pi}{6} + \theta) \cdot T_s \\ T_0 &= T_s - T_i - T_{i+1} \end{aligned} \tag{2}$$

B. *Circuit analysis*

According to the power balance between three phase input and dc output, in CSR, the relationship between output dc voltage (V_{dc}), rms value of input phase voltage (V_{srms}), power factor ($\cos\phi$), and modulation index (m) can be expressed as:

$$V_{dc} = \frac{3\sqrt{3} m \cos\phi V_{srms}}{2\sqrt{2}} \tag{3}$$

For a given power factor input, equation (3) indicates that conventional CSR is a buck converter and increasing m leads to higher output dc voltage. It is notable that if $\cos\phi$ >0, the energy can be regenerated from output to input. But $\cos\phi$ <0 in CSR and the input voltage can not change polarity, so CSR is unidirectional.

III. CURRENT-FED Z-SOURCE PWM RECTIFIER

A. *Current-fed Z-source PWM rectifier SVPWM Control strategy*

Besides the aforementioned nine possible states in CSR, the current-fed Z-source PWM rectifier has an extra open zero state which can be assumed by turning OFF all the upper switches or all the lower switches. SVPWM control can be consistently used in current-fed Z-source PWM rectifier. However, the difference in control is to turn some of the short zero state into open zero state, while keep the active state unchanged.

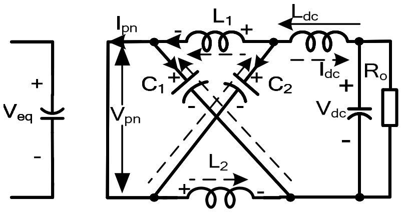
B. *Operating principle*

Fig. 2 shows the equivalent circuits of the current-fed Z-source PWM rectifier, where rectifier bridge becomes an equivalent voltage-source (V_{eq}). The solid arrows in Fig.2 define the positive direction of the current in L_1, L_2, C_1, C_2, L_{dc} and the dotted arrows shows the actual direction in rectification operation. The sign + and – shows the defined positive direction of the voltage. In state I, short zero state, the rectifier bridge is equivalent to a short circuit, the dc-link voltage V_{pn} is zero, and the diode D is off because the voltage on the diode is equal to two times of the capacitor voltage which is a negative value. In state II, active state, shown in Fig. 2(b), the dc-link voltage V_{pn} is equal to V_{eq} and the diode D is off because the V_{eq} is negative in rectification operation; in state III, open zero state, shown in Fig. 2(c), the rectifier is equivalent to an open circuit and the diode D is on which makes $V_L = V_C$. In all three states, the following equations are satisfied, assuming the Z-network has symmetric parameters that $C_1 = C_2 = C, L_1 = L_2 = L$:

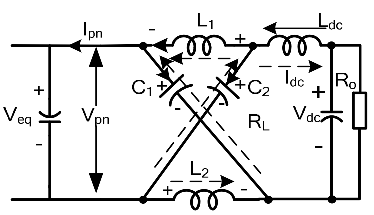
$$V_{C1} = V_{C2} = V_{dc}, V_{pn} = V_C - V_L, V_D = 2V_C - V_{pn} \tag{4}$$

In SVPWM control, the instantaneous value of V_{eq} in one sector can be expressed as follows:

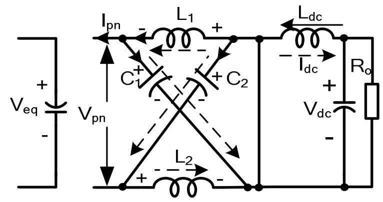
$$V_{eq} = \frac{T_1 \cdot v_{ab} + T_2 \cdot v_{ac}}{T_1 + T_2} = \frac{\frac{3\sqrt{2}}{2}\cos\phi}{\sin\theta} V_{srms} \tag{5}$$



(a). State I – Short Zero:D_{sh}



(b). State II—Active:D_A



(c). State III—Open Zero:D_{op}

Fig. 2.Operation states of current-fed Z-source PWM rectifier

, where V_{srms} is the rms value of the input phase voltage ; ϕ is the angle between input voltage and current; θ is the angle of the current reference vector; V_{eq} contains dc value and 6 ω voltage ripple and changes with phase angle, nevertheless, the average value in every sector is constant, calculated as:

$$\overline{V_{eq}} = \left(\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} \frac{\frac{3\sqrt{2}}{2} V_{srms}\cos\phi}{\sin\theta}\right) / \frac{\pi}{3} = \frac{\sqrt{2}\pi}{2} V_{srms}\cos\phi \tag{6}$$

When the rectifier input voltage and current has unity power factor, $\cos\phi = -1$, the average equivalent voltage is $\overline{V_{eq}} = -\sqrt{2}\pi V_{srms}/2$, which is always a negative value in rectification operation.

C. *Circuit analysis*

D_{sh}, D_A, D_{OP} are the duty ratios of state I, state II, and state III respectively. Obviously that $D_{sh}+D_A+D_{OP}=1$. According to equation (4),

In state I, $V_{pn} = 0, \quad V_C = V_L, V_{L_{dc}} = V_{dc} - 2V_c = -V_{dc}$;

In state II, $V_{pn} = V_{eq}, V_{L_{dc}} = V_{dc} - 2V_C + V_{eq} = V_{eq} - V_{dc}$;

In state III, $V_{L_{dc}} = V_{dc}$;

The average voltage on L_{dc} in an overall switching period is zero. So from voltage seconds balance, one has:

$$-V_{dc} \cdot D_{sh} + (V_{eq} - V_{dc}) \cdot D_A + V_{dc} \cdot D_{op} = 0$$

$$V_{dc} = \frac{D_A}{D_A + D_{sh} - D_{OP}} V_{eq} = \frac{D_A}{1 - 2D_{OP}} V_{eq} \tag{7}$$

So the voltage gain is

$$\frac{V_{dc}}{V_{eq}} = \begin{cases} D_A & D_{OP} = 0 \\ \dfrac{D_A}{2D_A - 1} & D_{sh} = 0 \end{cases} \tag{8}$$

Fig. 3 graphically illustrated the voltage gain versus D_A , in case 1 ,without any open zero states and in case 2, turning entire short zero states to open zero states. When turning parts of short zero states into the open zero states, the voltage gain will be in the shadow operation region. Voltage gain can not be positive because it can cause the diode improperly conducting in state I. Diode Voltage is $V_D = 2V_C - V_{pn}$ .In state I, $V_{pn} = 0$, $V_D = 2V_C = 2V_{dc}$; When D_A is 0~0.5, $V_{dc}/V_{eq} < 0$ and when D_A is 0.5~1, $V_{dc}/V_{eq} > 0$. For rectifier, $V_{eq} < 0$ because $\cos\phi = -1$ and V_{eq} is reversed. So in order to get positive V_{dc} to prevent diode from unexpected conducting,