A Strategy of Direct Power Control for PWM Rectifier Reducing Ripple in Instantaneous Power

T. Mohammed Chikouche, K. Hartani

Abstract—In order to solve the instantaneous power ripple and achieve better performance of direct power control (DPC) for a three-phase PWM rectifier, a control method is proposed in this paper. This control method is applied to overcome the instantaneous power ripple, to eliminate line current harmonics and therefore reduce the total harmonic distortion and to improve the power factor. A switching table is based on the analysis on the change of instantaneous active and reactive power, to select the optimum switching state of the three-phase PWM rectifier. The simulation results show feasibility of this control method.

Keywords—Power quality, direct power control, power ripple, switching table, unity power factor.

I. INTRODUCTION

In recent years, three-phase PWM rectifiers have been widely applied in many variety of industrial applications due to its advantages, such as absorption of sinusoidal current with low harmonic distortion and the possibility of operation with a power factor unity, good DC-bus voltage regulation ability and bidirectional power flow [1]-[3].

Various control strategies are proposed in [4]-[6] which are classified into two categories: (1) Voltage Oriented Control (VOC) similar to the vector control of electrical machines [7]-[9], and (2) DPC similar to the direct torque control of electrical machines [10]. These strategies reach the same goals, such as the unity power factor and the sinusoidal input current waveform, but their principles are different. This method has some disadvantages such as coupling which occurs between the active and reactive components and the problem of coordinate transformation. However, the DPC controls the active and reactive power directly. Compared to VOC, the DPC can achieve very quick response with simple structure by selecting a voltage vector from predefined switching table. The latter is not accurate for it gives large power ripples [11], [12].

The main advantages of DPC are absence of coordinate transformation, no internal current control loop and no PWM modulator block. In the conventional DPC [13], the active and reactive power are estimated using grid voltage and current measurements based on instantaneous power theory [14]. The hysteresis band control technique is used to compare instantaneous errors of active and reactive power. The output of the two hysteresis controller and the position of the voltage vector constitute the inputs of the switching table which imposes the switching state of the PWM rectifier [15], [16].

The disadvantages of conventional DPC are high active power ripple and slow transient response to the step changes in power load. The switching table has a very important role in the performance of the DPC [17]. However, the use of only one voltage vector in the conventional switching table during one control period leads to high power ripples. The conventional switching table illustrated in [18], demonstrates that it is not satisfactory in the controlling of the active and reactive power.

The main aim of this paper is to propose a switching method for DPC to improve DC-bus voltage regulation by directly controlling the instantaneous active and reactive power, eliminate the harmonic current and achieve a unity power factor operation.

This paper is arranged as follows: A model of a three-phase rectifier is presented in section two. A principle of the proposed DPC with a switching table is carried out based on the analysis of the instantaneous active and reactive power, including steady state performance, dynamic response and robustness against external load disturbance. Simulations by using MATLAB/Simulink are performed to study the characteristics and performance of the proposed method under steady state and transient conditions. To conclude, there is a thorough conclusion.

II. MODEL OF THREE-PHASE PWM RECTIFIER

The topology of three-phase bidirectional voltage-source PWM rectifier (VSR) is shown in Fig. 1. The VSR is connected to the three-phase AC source via smoothing LC link capacitor. Insulated Gate Bipolar Transistor (IGBTs) are used as the VSR power switches since IGBTs have features of high frequency switching applications. The DC-link capacitor C is used for filtering the ac components so that DC voltage with minimum ripple can be achieved at the output of VSR. It is assumed that a pure resistive load $R_L$ is connected at the DC-link capacitor C [19].

The model of the PWM rectifier can be expressed in $(a,b,c)$ frame as:

$$
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix} =
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} R + \begin{bmatrix}
dv_a \\
dv_b \\
dv_c
\end{bmatrix} + \begin{bmatrix}
v_{ra} \\
v_{rb} \\
v_{rc}
\end{bmatrix}
$$

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The phase voltage at the poles of the converter is equal to:

\[
\begin{bmatrix}
 v_{ra} \\
 v_{rb} \\
 v_{rc}
\end{bmatrix} = \frac{1}{3}
\begin{bmatrix}
 2 & -1 & -1 \\
 -1 & 2 & -1 \\
 -1 & -1 & 2
\end{bmatrix}
\begin{bmatrix}
 S_a \\
 S_b \\
 S_c
\end{bmatrix}
\]

(3)

The instantaneous apparent power can be expressed in several different manners as (4):

\[
S = \bar{i} v = p + j q = v_a i_a + v_b i_b + v_c i_c + \frac{1}{\sqrt{3}} \left[(v_b - v_c) i_a + (v_c - v_a) i_b + (v_a - v_b) i_c\right]
\]

(4)

where \( \bar{i} \) is the complex conjugate of line current \( i \); \( j \) is the imaginary unit.

The instantaneous active power and reactive power at the grid side can be calculated from grid voltage and current as [20], [22]:

\[
\begin{aligned}
p &= v_a i_a + v_b i_b + v_c i_c \\
q &= \frac{1}{\sqrt{3}} \left[(v_b - v_c) i_a + (v_c - v_a) i_b + (v_a - v_b) i_c\right]
\end{aligned}
\]

(5)

From the power model of PWM rectifier, we can know that different switching states have different influences on the active and reactive power. It is possible to select proper switching states to adjust the active and reactive power.

III. SWITCHING TABLE FOR DPC

A. Principle of the DPC

The DPC technique is based on the direct control of active and reactive power of PWM rectifier. The instantaneous values of active \( p \) and reactive \( q \) power are estimated by (4). The active power reference is obtained from the voltage controller of the DC bus. However, the reactive power reference is set to zero to get unity power factor.

As shown in Fig. 2, the output of the two hysteresis controllers constitutes the inputs of the proposed switching table which selects the optimal switching states of PWM rectifier [10]-[14].

The digitized signals \( S_p, S_q \) which are provided by a fix band hysteresis comparator can show whether should increase or reduce (decrease) the active or reactive power.

B. Vector Selection in the Switching Table

The switching table is formed from the output of the two hysteresis controllers \( (S_p, S_q) \) and the angular position \( \theta_n \) of the voltage vector. \( S_p = 1 \) stands for the need to increase the active power, while \( S_p = 0 \) denotes the need to decrease the active power. So, it is the case of the \( S_q \).

\[
(n - 2)\frac{\pi}{6} \leq \theta_n \leq (n - 1)\frac{\pi}{6} \quad n = 1, 2, ..., 12
\]

(7)
According to the inputs $S_p$ and $S_q$, together with the sector information, the proper rectifier input voltage vector can be chosen and the corresponding switching stable will be sent to trigger the IGBTs of the main circuit.

Considering the value of $R$ is small enough to be neglected, the instantaneous active and reactive power can be rewritten as:

\[
\begin{align*}
\frac{dp}{dt} &= \frac{3}{2} \frac{L}{L} \frac{V_d^2}{L} - \frac{V_d v_{dc}}{L} \cos\left(\omega t - \frac{\pi}{3}(k-1)\right) \\
\frac{dq}{dt} &= \frac{V_d v_{dc}}{L} \sin\left(\omega t - \frac{\pi}{3}(k-1)\right) + \omega p
\end{align*}
\]  

(8)

where $k = 1, 2, 3, 4, 5, 6$, corresponding to the no zero selected voltage number shown in Fig. 3.

The variation of active power and reactive power versus grid voltage position for various rectifier voltage vectors are depicted in Fig. 4.

In order to achieve better performance of system, the switching table should be synthesized based on the variation of active and reactive power for various rectifier voltage vectors in each sector, as shown in Fig. 4. Take the first three sectors for example, the signs of slope in active and reactive power are illustrated in Table I [22].

The switching table for DPC of PWM rectifier can be summarized in Table II.

**TABLE I**

<table>
<thead>
<tr>
<th>Sector</th>
<th>$\phi S_1 = 0$</th>
<th>$\phi S_2 = 0$</th>
<th>$\phi S_3 = 0$</th>
<th>$\phi S_4 = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_1$</td>
<td>$V_1, V_2, V_3, V_4$</td>
<td>$V_1, V_2, V_3, V_4$</td>
<td>$V_1, V_2, V_3, V_4$</td>
<td>$V_1, V_2, V_3, V_4$</td>
</tr>
<tr>
<td>$\theta_2$</td>
<td>$V_5, V_6, V_7, V_8$</td>
<td>$V_5, V_6, V_7, V_8$</td>
<td>$V_5, V_6, V_7, V_8$</td>
<td>$V_5, V_6, V_7, V_8$</td>
</tr>
<tr>
<td>$\theta_3$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
</tr>
<tr>
<td>$\theta_4$</td>
<td>$V_1, V_2, V_3, V_4$</td>
<td>$V_1, V_2, V_3, V_4$</td>
<td>$V_1, V_2, V_3, V_4$</td>
<td>$V_1, V_2, V_3, V_4$</td>
</tr>
<tr>
<td>$\theta_5$</td>
<td>$V_5, V_6, V_7, V_8$</td>
<td>$V_5, V_6, V_7, V_8$</td>
<td>$V_5, V_6, V_7, V_8$</td>
<td>$V_5, V_6, V_7, V_8$</td>
</tr>
<tr>
<td>$\theta_6$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
</tr>
<tr>
<td>$\theta_7$</td>
<td>$V_1, V_2, V_3, V_4$</td>
<td>$V_1, V_2, V_3, V_4$</td>
<td>$V_1, V_2, V_3, V_4$</td>
<td>$V_1, V_2, V_3, V_4$</td>
</tr>
<tr>
<td>$\theta_8$</td>
<td>$V_5, V_6, V_7, V_8$</td>
<td>$V_5, V_6, V_7, V_8$</td>
<td>$V_5, V_6, V_7, V_8$</td>
<td>$V_5, V_6, V_7, V_8$</td>
</tr>
<tr>
<td>$\theta_9$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
<td>$V_9, V_{10}, V_{11}, V_{12}$</td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
<th>$S_p$</th>
<th>$S_q$</th>
<th>$\theta_1$</th>
<th>$\theta_2$</th>
<th>$\theta_3$</th>
<th>$\theta_4$</th>
<th>$\theta_5$</th>
<th>$\theta_6$</th>
<th>$\theta_7$</th>
<th>$\theta_8$</th>
<th>$\theta_9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>$V_1$</td>
<td>$V_2$</td>
<td>$V_3$</td>
<td>$V_4$</td>
<td>$V_5$</td>
<td>$V_6$</td>
<td>$V_7$</td>
<td>$V_8$</td>
<td>$V_9$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>$V_5$</td>
<td>$V_6$</td>
<td>$V_7$</td>
<td>$V_8$</td>
<td>$V_9$</td>
<td>$V_{10}$</td>
<td>$V_{11}$</td>
<td>$V_{12}$</td>
<td>$V_1$</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>$V_1$</td>
<td>$V_2$</td>
<td>$V_3$</td>
<td>$V_4$</td>
<td>$V_5$</td>
<td>$V_6$</td>
<td>$V_7$</td>
<td>$V_8$</td>
<td>$V_9$</td>
</tr>
</tbody>
</table>

**C. Control of the DC-Link Voltage**

The basic operation principle of VSR is to regulate the DC-link voltage $v_{dc}$ at load, at a reference value $v_{dc}^*$, while maintaining a desired grid side power factor. The value of $v_{dc}^*$ has to be high enough to keep the diodes of converter blocked and maintain the controller stability.

Generally, the minimum DC-link voltage can be determined by the peak value of line-to-line grid, i.e. $v_{dc} > \sqrt{3} \sqrt{ with \text{V}_{\text{ RMS}}} = 2.45V_{\text{ RMS}}$

$V_{dc} = \sqrt{3} \sqrt{v_{\text{RMS}}} = 2.45V_{\text{RMS}}$

The error between rectified voltage $v_{dc}$ and reference $v_{dc}^*$ is then fed to the anti-windup IP controller to obtain the current component command $i_{dc}^*$ [19]. The product of rectifier voltage $v_{dc}$ and the current reference obtained at the output of the anti-windup IP controller gives the active power reference.
TABLE III  
ANTI-WINDUP ALGORITHM

Err=Vdc_ref-Vdc;
Tintegral(n+1)=Tintegral(n)+ki*T*Err;
idc_ref=kp*(Tintegral(n+1)- Vdc);
if abs(idc_ref)>=abs(idc_max)
  idc_ref =sign(idc_ref)*idc_max;
  Tintegral(n+1)=idc_ref /kp+ Vdc;
End;

IV. RESULTS AND DISCUSSION

To evaluate the performance of the proposed DPC with switching table, the simulation test is carried out on a two-level three-phase PWM rectifier. In this simulation test, we have introduced some changes the reference of the DC bus voltage (between $t=0.30s$ and $t=0.70s$), and then introduced a perturbation characterized by a load resistance increasing between the instant $t=0.45s$ and $t=0.55s$. The main parameters of the simulation circuit are given in Table IV.

TABLE IV  
RECTIFIER PARAMETERS

The input phase voltage: $V=125V$ / $f=50Hz$
The input inductance: $L=37mH$
The input resistance: $R=0.3\Omega$
The output capacitor: $C_{dc}=1100\mu F$
The output voltage: $V_{dc}=350V$

Fig. 5 (a) shows simulation waveform that the load increases from $500\Omega$ to $750\Omega$ at $0.45s$ and at $0.55s$. We notice from Fig. 5 (b) that the response of the DC-bus voltage $v_{dc}$ follows perfectly its reference. There is a satisfactory steady state operation with no static error, which shows that the proposed analytical approach for the design of the IP regulator is fairly rigorous, Fig. 5 (c). The application of the disturbance affects the DC bus voltage with a weak drop of the order of $0.3\%$ for a brief period of $0.05\ s$, Fig. 5 (c). This signifies that the voltage IP regulator acts well on the rejection of this disturbance. To show the efficiency of the IP regulator, the normalized error of the DC bus voltage is shown in Fig. 5 (d).

The introduction of the perturbation characterized by an increase in the load resistance applied at the instant $t=0.45s$ in steady state causes a decrease in the load current which responds instantaneously to this variation and after the instant $t=0.55s$, the current $i_L$ is kept constant at its nominal value $0.9A$, Fig. 5 (e).

The current response is practically instantaneous, as shown in Fig. 6 (a), which represents the three currents at the input of the rectifier corresponding to the current operation. In transient mode, these currents show a transient with a rapid increase when the load is applied. Then, they stabilize at an amplitude of $1.55A$ after the instant $t=0.55s$, Fig. 6 (b). We notice that these grid currents are sinusoidal which gives a low rate of harmonic distortion. Fig. 6 (c) shows the harmonic spectrum of the response of the grid current $i_d$. It is noted that all the low render harmonics are well attenuated, which gives a rate of harmonic distortion (THD =0.96%).
**Fig. 5** Simulation result of the PWM rectifier with under load disturbance (50% variation of resistance at 0.45s and 0.55s)

- **(d) Normalized error of the DC output voltage**
  - Normalized error of the DC output voltage over time.

- **(e) Load current**
  - Load current over time.

**Fig. 6** The waveforms of three phase grid current and line current spectrum

- **(a) Line current**
  - Waveform of phase a line current.

- **(b) Zoom of line current**
  - Detailed view of phase a line current.

- **(c) Line current spectrum of phase a**
  - Spectrum of phase a line current.

- **(i) **Zoom of line current spectrum**
  - Spectrum zoom for phase a.

**Fig. 7** Voltage and current waveforms of phase a

- **(a) Line current**
  - Waveform of phase a line current.

- **(b) Zoom of line current**
  - Detailed view of phase a line current.

- **(c) Grid voltage (V) vs current (A)**
  - Grid voltage and current waveform.

**Fig. 7** shows that the grid current $i_a$ is phase with the grid voltage, which gives a unit power factor.
The power response is illustrated in Fig. 8. The active power increases from 245 W to 406 W at $t = 0.4 s$, and then decreases to 270 W between $t = 0.45 s$ and $t = 0.55 s$, and then increases to 406 W. After $t = 0.37 s$, it stabilizes at the initial value (245 W).

The proposed DPC with a switching table adjusts well the active power in all sectors when the load power decreases. It is clearly seen that in Fig. 8, the reactive power is kept at zero to achieve a unit power factor. It can be seen that the proposed DPC achieves a decoupled control of active and reactive power. It can be seen that the proposed DPC achieves a decoupled control of active and reactive power. The simulation results prove that the proposed DPC is much better when the load changes.

![Fig. 8 Voltage and current waveforms of phase α](image)

V. CONCLUSION

This paper introduces a control method for DPC of three-phase PWM rectifier based on the analysis of instantaneous active and reactive power. The proposed method can choose a more appropriate switching state. Hence, it can eliminate line current harmonics, reduce the total harmonic distortion, achieve unity power factor, and keep the instantaneous active and reactive power and DC-bus voltage at their desired values. Simulation results show a good performance of proposed method and provide a good regulation of output DC voltage and give better performances in steady state and dynamic response disturbance rejection.

REFERENCES


