Research of Three Phase PWM Rectifier based on Direct Vector Control Method

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Abstract: In oilfield worldwide, beam pumping units are wildly used to produce oil. the working mechanism of beam pumping unit determines that its driving motor frequently enters into the state of power generation, so PWM reversible rectifier is an ideal choice for recycle the generated energy, therefore it is necessary to research the control theory of PWM reversible rectifier. The paper presents a digital algorithm for the PWM rectifier, on the basis of coordinate analyzing theory and SVPWM method. The method that directly calculates the basic vector operation time and position is adopted, so the arc-tangent calculation is avoided, calculation process is simplified. Based on the vector coordinate transformation of three-phase reversible PWM rectifier, the control equation of direct current control method is derived in this paper. The rectifier control algorithm is realized with high performance DSP TMS320F28335. The experimental results prove that the method proposed in the paper is practical and correct.

1. Introduction
In the field of AC drive, the motor often enters into generation state, while reversible PWM rectifier can use the energy generated by AC motor. It can not only realize regenerative braking and improve the speed regulation performance, but also recover the considerable electric energy generated in the power generation state, ensure the power factor equal to 1, and eliminate the pollution of nonlinear load on the power grid. In the field of petroleum industry, the working mechanism of beam pumping unit determines that its driving motor frequently enters into the state of power generation, so PWM reversible rectifier is an ideal choice for recycle the generated energy.

As an effective measure to suppress harmonics, PWM technology has been used in converter power supply for a long time. If PWM technology is introduced into rectifier, the unit power factor and the input current close to sine can be obtained. The voltage space vector PWM technology has been widely used in the field of transmission because of its high utilization rate of DC voltage and easy digital realization.

Based on the vector coordinate transformation of three-phase reversible PWM rectifier, the control equation of direct current control method is derived in this paper. Combined with input voltage space vector modulation, a control algorithm which is convenient for digital implementation is proposed. The digital control of PWM reversible rectifier is realized by DSP.

2. Control strategy of 3-phase PWM reversible rectifier
The main circuit structure of three-phase PWM reversible rectifier is shown in Figure 1. In the three-phase static coordinate system, the voltage and current satisfy the following equation:
For the convenience of control and analysis, the coordinate transformation (3s / 2r) from three-phase static (3s) to two-phase d-q-axis rotation (2r) is carried out in equation (1). Assuming that the rotation speed of d-q axis is \( \omega \) and rotates synchronously with the voltage space vector \( \vec{E} \) in 3s system, the three AC component in 3s system is transformed into DC component in 2r system, \( e_d = E_d \), \( e_q = E_q \) and the transformation matrix of 3s/2r transformation is as follows:

\[
C_s = \begin{bmatrix}
\frac{2}{3} \cos(\alpha) & \cos(\alpha - 120^\circ) & \cos(\alpha + 120^\circ) \\
-\sin(\alpha) & -\sin(\alpha - 120^\circ) & -\sin(\alpha + 120^\circ)
\end{bmatrix}
\]

By applying the inverse matrix \(^1\) of equation (2), we can obtain that:

\[
\begin{bmatrix}
e_d \\
e_q \\
e_c
\end{bmatrix} = C_s^{-1} \begin{bmatrix}
e_d \\
e_q \\
e_c
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
e_d \cos(\alpha) - e_q \sin(\alpha) \\
e_d \cos(\alpha - 120^\circ) + e_q \sin(\alpha - 120^\circ) \\
e_d \cos(\alpha + 120^\circ) - e_q \sin(\alpha + 120^\circ)
\end{bmatrix}
\]

By comparing the two formulas, it can be seen that if the component \( e_q \) and \( e_d \) are zero, the three-phase current and voltage in 3s system are in the same phase, that is, \( pf = 1 \). If \( I_d < 0 \), it means...
that the current and voltage are in inverse phase, pf = -1, and the converter is in generative state.

From equation (3), we can get

$$e_d = \frac{2}{\sqrt{3}} (e_d \cos \omega t - e_q \sin \omega t)$$  \hspace{1cm} (6)$$

By substituting equation (6) into equation (1), we can get following equation:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} -R & \omega L \\ -\omega L & -R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} e_d \\ e_q \end{bmatrix}$$  \hspace{1cm} (7)$$

In order to realize the direct control of the current, the current feedback control parameter is introduced

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = K_i \begin{bmatrix} i_d^* - i_d \\ i_q^* - i_q \end{bmatrix} + \begin{bmatrix} -R & \omega L \\ -\omega L & -R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} e_d \\ e_q \end{bmatrix}$$  \hspace{1cm} (8)$$

Where, $i_d^*$ and $i_q^*$ are given quantity, $K_i$ is current regulation factors.

In order to facilitate the space vector modulation, the 2s/2r transform of equation (8) is performed, and then the 2s/2r inverse matrix is multiplied on the left.

$$C_{2r/2s} = \begin{bmatrix} \cos \omega t & -\sin \omega t \\ \sin \omega t & \cos \omega t \end{bmatrix}$$  \hspace{1cm} (9)$$

Then the control equation of three-phase PWM reversible rectifier is obtained

$$\begin{bmatrix} v_a \\ v_B \end{bmatrix} = K_i \begin{bmatrix} i_a^* - i_a \\ i_B^* - i_B \end{bmatrix} + \begin{bmatrix} -R & \omega L \\ -\omega L & -R \end{bmatrix} \begin{bmatrix} i_a \\ i_B \end{bmatrix} + \begin{bmatrix} e_a \\ e_B \end{bmatrix}$$  \hspace{1cm} (10)$$

The equation (1) can be obtained by 3s/2s transformation.

$$\begin{bmatrix} e_a \\ e_B \end{bmatrix} = L \frac{di_a}{dt} + Ri_a + v_a \\ e_B = L \frac{di_B}{dt} + Ri_B + v_B$$  \hspace{1cm} (11)$$

It is easy to know that the physical meaning of formula (10) and formula (11) are the same, but their forms are different. However, formula (10) is more convenient than formula (11) in realizing the system, because it avoids derivative operation and is easy to realize digitally.

### 3. Voltage space vector PWM algorithm

In the three-phase rectifier bridge shown in Fig. 1, there are six groups of effective switching vectors and two zero vectors. Their positions in the coordinate system are shown in Fig. 2.

If vector $\bar{V}$ is located in the sector surrounded by the basic space vector $\bar{V}_0$ and basic space vector $\bar{V}_{60}$, it can be represented by these two basic vectors, and their action time is:
In formula (12), $m$ is the modulation depth, $m = \sqrt{3} \left[ \sqrt{U_{dc}} \cdot |\vec{V}| \right]$ is the mode of the neutral point voltage space vector $\vec{V}$ of the bridge arm, $T_1$ and $T_2$ are action time of basic space vector $V_0$ and $V_{60}$ in the cycle time $T_p$, and $T_0$ is the action time of the zero vector.

In Figure 2, if $v_\alpha$ and $v_\beta$ in the 2s system is known, the position angle relative to the coordinate axis is: $\gamma = \arctg \frac{v_\alpha}{v_\beta}, \gamma \in [0,360^\circ]$, according to the sector where the voltage space vector is located, due to the complexity of arctangent calculation, it is difficult to realize it with DSP. The reference voltage method in equation (13) can be used to determine the sector of $\vec{V}$ [3].

The corresponding relationship between $N$ and sector number is shown in the table below:

| $N$ | 1 | 2 | 3 | 4 | 5 | 6 |
|-----|---|---|---|---|---|---|
| sector | 2 | 6 | 1 | 4 | 3 | 5 |

For convenient, variables $a,b,c$ are defined.

if $V_{ref1} > 0$, then $a = 1$, else $a = 0$,

if $V_{ref2} > 0$, then $b = 1$, else $b = 0$,

if $V_{ref3} > 0$, then $c = 1$, else $c = 0$.

Define $N = 4\cdot c + 2\cdot b + a$. The corresponding relationship between $N$ and sector number is shown in the table below:

Then, the action time of the two basic vectors can be calculated by formula (14):

$$T_1 = \frac{T_p}{2} \cdot \frac{3v_\alpha}{U_{dc}} - \frac{\sqrt{3}v_\beta}{U_{dc}}$$

$$T_2 = T_p \frac{v_\beta}{U_{dc}}$$

$$T_0 = T_p - T_1 - T_2$$

4. Composition of closed loop control system

According to the vector transformation relation and control equation of the three-phase PWM reversible rectifier, a double closed-loop control system of the converter can be formed. The control block diagram of the system is shown in Fig. 3. The output of DC side of the three-phase PWM
5. Digital realization and experimental results based on TMS320F28335

In this paper, the chip TMS320F28335 produced by TI company is used as the control core of the system. The control block diagram of the system is shown in Figure 3. The sampling circuit carries out the grid voltage and input phase current, and converts them into analog signals within the A/D port of DSP. DSP completes the core control tasks such as A/D conversion, coordinate transformation, PI adjustment, space vector, etc. the space vector state machine of F28335 DSP is sent out Six PWM pulses are used to control the main circuit IGBT through the driver board.

A three-phase PWM reversible rectifier prototype is developed by using the above method. The switching device adopts the bsm200gb120dcl IGBT module of Mitsubishi Company. The filter inductance of the incoming line is 4, the resistance is ignored, and the filter capacitance of the DC side bus is. The experimental parameters are as follows: phase voltage, DC voltage, load resistance, switching frequency.

Fig. 3 Control block diagram of three phase PWM reversible rectifier
The experimental results are shown in Fig. 4 and Fig. 5. Fig. 4 shows the phase relationship between the offline voltage and the phase current in the rectifier state in steady state, which is 30 degrees ahead of each other. It can be seen that the phase voltage and phase current are in the same phase, the power factor is close to 1, and the current waveform is approximately sinusoidal. It can be seen from Figure 5 that the DC voltage is basically constant when the load is suddenly reduced. The good static and dynamic response characteristics of PWM reversible rectifier are shown.

6. Conclusion
On the basis of vector coordinate transformation of three-phase PWM reversible rectifier, the control equation of direct current control method is derived. By directly calculating the action time of the basic vector of neutral point voltage vector in the synthetic bridge arm in each sector, the arc-tangent operation is avoided and the calculation process is simplified. The three-phase PWM is manufactured and debugged with TMS320F240 as the control core. The experimental results of a prototype of reversible rectifier verify the effectiveness of the control algorithm.

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