Study of Multi-level Rectifier in High Power System Based on a Novel Virtual Flux Observer

Yaofei Han, Guojun Tan, Hao Li, Xuanqin Wu
China University of Mining and Technology
South Jiefang Road, 221008 Xuzhou, Jiangsu, China
hanyaofei@yahoo.com.cn

Abstract — In the control of PWM rectifier, it can restrain harmonic and interference effectively by constructing a virtual line-flux-linkage to serve as the oriented vector. However, there are some problems in the conventional method, such as the error of amplitude, the shift of phase angle and the nondeterminacy of initial oriented angle. In the thesis, two one-stage low-pass filters are adopted instead of the pure integrator in the virtual line-flux-linkage observer, which can steady the phase and amplitude. Furthermore, a novel method of voltage estimate at the three-level rectifier terminals is advanced based on the simplified SVPWM algorithm. The good dynamic and static performance under the proposed control strategy is verified by simulation and experiment.

Index Terms -- Multi-level, PWM rectifier, virtual flux observer, voltage estimator.

I. INTRODUCTION

PWM Rectifiers, as a type of non-polluting equipment, are going to be more popular in the high power system, especially in which demands dual energy flow, three-level topology has been applied in several situations, such as APF · SMES · ED · HVDC and UPFC etc [1].

In the dual closed-loop line voltage oriented vector control of PWM rectifier, it neglects harmonic current and that will cause the incurrence of oriented angle. The traditional virtual line flux strategy will lead to a large current rush due to the nondeterminacy of initial oriented angle. A novel vector control oriented by virtual line flux and located by precise initial angle is suggested in this thesis, which combines advantages of the both. The proposed scheme can restrain harmonic and interference effectively, which is the most promising application equipment in high power system [2].

II. PROPOSED SCHEME

Three-level inverter is high power inverter which roots from Germany scholar named Holtz in 1977. Japanese scholar named Noble A and his colleagues improved the three-level inverter in 1980. They replaced the auxiliary switches with a pair of diodes. And this topology was applied to rectifier rapidly. Topology of three-level voltage source rectifier (VSR) is showed in Fig. 1. 

According to [3] [4], if the incoming reactor and line resistance are neglected, the voltage equation of three-phase in reference frame is:

$$
\begin{align*}
\psi_\alpha' &= L \frac{d \psi_\alpha}{dt} + u_\alpha \\
\psi_\beta' &= L \frac{d \psi_\beta}{dt} + u_\beta
\end{align*}
$$

(1)

Integrated both sides of (1), it can obtain:

$$
\begin{align*}
\int e_\alpha dt &= \int \left( L \frac{d \psi_\alpha}{dt} + u_\alpha \right) dt \\
\int e_\beta dt &= \int \left( L \frac{d \psi_\beta}{dt} + u_\beta \right) dt
\end{align*}
$$

(2)

define $\int e_\alpha dt = \psi_\alpha, \int e_\beta dt = \psi_\beta$, (2) becomes:

$$
\begin{align*}
\psi_\alpha &= \int u_\alpha dt + L \psi_\alpha \\
\psi_\beta &= \int u_\beta dt + L \psi_\beta
\end{align*}
$$

(3)

In (3), $\psi_\alpha, \psi_\beta$ present the $\alpha, \beta$ value of virtual line flux one by one.

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Fig. 1. Circuit diagram of three-level NPC converter

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B. The Novel Virtual Line Flux Observer

Low-pass filter is adopted by conventional virtual line-flux to substitute for the purely integrator to least the DC drift, however, it would lead to errors of amplitude and phase angle as describe in [4][5].

In order to replace the segment of pure integrator, it demands neither error of amplitude nor the shift of phase (the shift of phase is 90°which equals to that of pure integrator).

\[ W(s) = \frac{N}{s + \omega_c} - \frac{N}{s + \omega_c} \]

(4)

According to the previous criteria and (4), \( N = \sqrt{2\omega} \) and \( \omega_c = \omega \) are obtained. The novel virtual line flux observer and the comparison of the three observers are showed in Fig.2 and Fig. 3 respectively, which distinctly show that the novel algorithm responds faster than the traditional control.

![Novel virtual line flux observer](image)

![Comparison of the three observers](image)

In the conventional control, the nondeterminacy of initial oriented angle will lead to a large current rush as the former description. This paper proposed an initial oriented estimation similarly to the observation of AC motor flux linkage. The accurate initial value is obtained by integrating power EMF, then the angle switches when the rectifier operates. The initial angle estimation and control diagram are showed as Fig. 4 and Fig. 5.

III. THE NOVEL VOLTAGE ESTIMATOR FOR MULTI-LEVEL RECTIFIER

According to (2), it should obtain the precise virtual line flux to calculate the voltage at the terminals of three-level rectifier.

The simplified SVPWM algorithm according to [6] showed in Fig. 6 is adopted. As shown in Fig.6, three-level space vector diagram can be considered to be constructed by six small hexes of conventional two-level space vector, and all the hexes are centered by vertexes of inner hex. Hence, two-level SVPWM algorithm can be applied to calculate the duration-time and the switch sequence of voltage vector. On the basis of the proposed algorithm, the voltage at the terminals of three-level rectifier is estimated, which is showed in Fig. 6.
As shown in Fig. 5, a new simplified three-level rectifier voltage reconstruction method can be regard as reconstruction the output voltage in a two-level.

The traditional two-level phase voltage can be expressed in terms of DC-bus voltage and duration-time two-level inverter or rectifier[7].

\[
V_{an} = V_{dc}(\frac{2}{3}T_a - \frac{1}{3}T_b + \frac{1}{3}T_c)/T_s
\]

\[
V_{bn} = V_{dc}(\frac{2}{3}T_b - \frac{1}{3}T_a + \frac{1}{3}T_c)/T_s
\]

\[
V_{cn} = V_{dc}(\frac{2}{3}T_c - \frac{1}{3}T_a + \frac{1}{3}T_b)/T_s
\]

where \( V_{an}, V_{bn}, \) and \( V_{cn} \) are the estimated voltage of two-level rectifier, \( V_{dc} \) is the DC-bus voltage, \( T_a, T_b \) and \( T_c \) are the duration-time of each phase and \( T_s \) is the carrier time.

As shown in [6], in order to transfer the estimated voltage of traditional two-level result into three-level, three-level space vector diagram can be considered to be constructed by six hexagons as shown in Fig. 6 and the coordinate transformation of three-level inverter must be done too[6].

So the same parameters in formula (5)-(7) can be get too. Furthermore, the location of reference voltage can be calculated. Take the first small hexagon shown as Fig.7 as an example to demonstrate this simplified three-level rectifier phase voltage estimation algorithm.

\[
V'_{an} = V_{dc}(\frac{2}{3}T_a - \frac{1}{3}T_b - \frac{1}{3}T_c)/T_s + V_{dc}/3
\]

\[
V'_{bn} = V_{dc}(\frac{2}{3}T_b - \frac{1}{3}T_a - \frac{1}{3}T_c)/T_s - V_{dc}/6
\]

\[
V'_{cn} = V_{dc}(\frac{2}{3}T_c - \frac{1}{3}T_b - \frac{1}{3}T_a)/T_s - V_{dc}/6
\]

As a result, three-level voltage estimator can be described as following:

\[
V'_{an} = V_{dc}(\frac{2}{3}T_a - \frac{1}{3}T_b - \frac{1}{3}T_c)/T_s + V_{a\_comp}
\]

\[
V'_{bn} = V_{dc}(\frac{2}{3}T_b - \frac{1}{3}T_a - \frac{1}{3}T_c)/T_s + V_{b\_comp}
\]

\[
V'_{cn} = V_{dc}(\frac{2}{3}T_c - \frac{1}{3}T_b - \frac{1}{3}T_a)/T_s + V_{c\_comp}
\]

where \( V'_{an}, V'_{bn}, \) and \( V'_{cn} \) are the estimated voltages of three-level rectifier, \( T_a, T_b \) and \( T_c \) are the duration-time of three-phase in two-level algorithm respectively. And \( V_{a\_comp}, V_{b\_comp} \) and \( V_{c\_comp} \) are compensation voltages of A, B and C phases which are related with the hexagon number of the reference voltage, it is the six little hexagon center voltage vectors’ projections on A, B and C axis respectively, as shown in Fig. 7 in hexagon 1.

<table>
<thead>
<tr>
<th>Number of little hexagon where the reference voltage located</th>
<th>Phase A compensation voltage</th>
<th>Phase B compensation voltage</th>
<th>Phase C compensation voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+Vdc/3</td>
<td>-Vdc/6</td>
<td>-Vdc/6</td>
</tr>
<tr>
<td>2</td>
<td>+Vdc/6</td>
<td>+Vdc/6</td>
<td>-Vdc/6</td>
</tr>
<tr>
<td>3</td>
<td>-Vdc/6</td>
<td>+Vdc/6</td>
<td>+Vdc/6</td>
</tr>
<tr>
<td>4</td>
<td>-Vdc/3</td>
<td>+Vdc/6</td>
<td>+Vdc/6</td>
</tr>
<tr>
<td>5</td>
<td>-Vdc/6</td>
<td>-Vdc/6</td>
<td>+Vdc/3</td>
</tr>
<tr>
<td>6</td>
<td>+Vdc/6</td>
<td>-Vdc/6</td>
<td>+Vdc/6</td>
</tr>
</tbody>
</table>

All the remaining procedures necessary for the three-level rectifier voltage estimation are done like that of two-level rectifier, only the different voltages called compensation voltages should be added in every different hexagon as shown in table 1.

IV. SIMULATION AND EXPERIMENT

To verify the viability of proposed control scheme and evaluate performance of this method, the paper constructed and operated the model using Matlab&Simulink. Based on the novel virtual line flux observer AFE, the dual PWM vector control system for doubly-fed motor is completed, which is applied in industry.
From the simulation and experiment, the novel virtual flux line oriented vector control can restrain interference and harmonic with the advantage of switching angles smoothly. Furthermore, under the adoption of this control, PWM rectifier has special characteristics of favorable dynamic and static performance as well as anti-interference.

V. CONCLUSIONS

The novel virtual line flux oriented vector control presented in this paper makes the observer no error of amplitude and no shift of phase, which also overcomes the nondeterminacy of the conventional virtual line flux oriented vector control. Moreover, the novel voltage estimation for multi-level rectifier is suggested based on simplified SVPWM algorithm of three-level topology. The simulation and experiment prove the feasibility of control scheme proposed by this paper and its excellent performance which is superior to the traditional vector control.

REFERENCES