Control the Three-level Rectifier Under Unbalanced Grid Conditions

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Abstract. This paper proposes a novel control method for Three-level rectifier under unbalanced grid conditions. An average model is established to analyze the influence of the unbalanced factor. It can be seen that the unbalanced factor will generate the negative-sequence current. The negative-sequence current can be suppressed by a proportional integral resonant (PIR) controller. Additionally, the unbalance of neutral-point (NP) voltage will generate in the three-level rectifier. Therefore, this paper proposes a space vector modulation for balancing the NP voltage. The simulation results confirm the performance and effectiveness.

Introduction

Three-phase pulse width modulation rectifier has been widely used in distributed generation systems. Traditionally, two-level rectifier was used as solution [1-3]. However, the two-level rectifier needs large filter for lower total harmonic distortion (THD). Therefore, this topology will increase the size and cost. In order to solve this problem, the three-level rectifier is chosen to substitute for two-level rectifier. The three-level rectifier has the advantage of lower THD which can decrease the size of filter [4-6]. Therefore, the topology using T-type is considered in this paper.

The operation of three-phase two-level converter in unbalanced condition is researched in [7]. However, the operation of three-level rectifier has not been paid attention. For parallel system, the negative-sequence circulating current is generated. In order to solve this key issue, a control method is proposed in [8].

In this paper, a novel control method is proposed for three-level rectifier under unbalanced condition. An average model is derived in in positive-sequence synchronous reference frame for analyze the influence of the unbalance grid voltage. The unbalanced grid voltage would lead to negative-sequence current. In order to suppress the negative-sequence current, this paper proposes a proportional integral resonant (PIR) controller. Moreover, the unbalance of neutral-point (NP) voltage will be generated in the three-level rectifier. Therefore, this paper proposes a space vector modulation for balancing the NP voltage. The effectiveness of the proposed method is verified by the simulations.

Model of Three-level Rectifier under Unbalanced Condition

The topology of three-level T-type rectifier is shown in Fig. 1. In order to analyze the influence of the unbalance condition of output currents, an model of the three-level rectifier is derived. Choosing the negative pole as the reference point, based on Kirchhoff’s voltage, the model under unbalanced operating conditions can be expressed as

\[
L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \\ u_o \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ e_o \end{bmatrix} = \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}
\]

where \( V_a, V_b \) and \( V_c \) are the output voltage, \( e_a, e_b, e_c \) are the grid voltage corresponding, \( i_a, i_b, i_c \) are the input currents, \( L \) is the filter of the rectifier.
Figure 1. Topology of three-level T-type rectifier.

Under unbalanced grid condition, the grid voltage can be expressed as

\[
\begin{bmatrix}
\epsilon_a \\
\epsilon_b \\
\epsilon_c
\end{bmatrix} = E_{nm} \begin{bmatrix}
\cos \omega t \\
\cos(\omega t + \frac{2}{3} \pi) \\
\cos(\omega t - \frac{2}{3} \pi)
\end{bmatrix} + E_{pm} \begin{bmatrix}
\cos \omega t \\
\cos(\omega t - \frac{2}{3} \pi)
\end{bmatrix}
\]

(2)

where \(\omega\) is the fundamental frequency, \(E_{nm}\) and \(E_{pm}\) are the positive-sequence and negative-sequence amplitude of grid voltage.

Therefore, the model of rectifier in the unbalanced condition can be expressed as

\[
\omega \left( L_{\text{sn}1} + \frac{1}{3} L_{\text{sn}2} \right) i_{ny} = \left( L_{\text{sn}1} + \frac{1}{3} L_{\text{sn}2} \right) \frac{di_{ny}}{dt}
\]

\[
+ u_y = \epsilon_d + \frac{L_{\text{sn}1}}{3L_{\text{sn}1} - L \cos \omega t} \left( \epsilon_y - u_y \right)
\]

\[
\omega \left( L_{\text{sn}1} - \frac{1}{3} L_{\text{sn}2} \right) i_{nx} + \left( L_{\text{sn}1} - \frac{1}{3} L_{\text{sn}2} \right) \frac{di_{nx}}{dt}
\]

\[
+ u_y = \frac{L_{\text{sn}1}}{3L_{\text{sn}1} + L \cos \omega t} \left( \epsilon_y - u_y \right) + \epsilon_y
\]

(3)

(4)

where \(\epsilon_y\) and \(\epsilon_d\) are the reactive power and reactive power grid voltage. \(L_{\cos 2nx}, L_{\cos px}, L_{\sin 2nx}, L_{\sin px}\) are the filter of \(2 \omega\) and \(\omega\).

Control of Negative-Sequence Current under unbalanced condition

To suppress the negative-sequence current, a novel method should be proposed to suppress the negative-sequence current. Conventionally, a PI controller is proposed for control active and reactive currents when the grid voltage is balance. However, under unbalanced grid voltage, the unbalanced condition will lead to unbalanced input current. Therefore, a negative-sequence component generates a \(2 \omega\) \textit{ac} component. The PI controller can be not suppressed the \textit{ac} component. To suppress the negative-sequence currents, proportional integral resonant (PIR) controller is proposed, which can be expressed as

\[
G(s) = \frac{k_r \omega_s}{s^2 + 2\omega_t s + \omega_r^2} + k_p + \frac{k_i}{s}
\]

(5)

where \(\omega_t = 2 \omega, k_r, k_p, k_i\) the resonance, proportion and integral resonance parameters are respectively.

The controller of T-type rectifiers under unbalanced condition can be expressed as
\[ u_q = \left( k_p + \frac{k_i \omega_L}{s^2 + 2 \omega_L s + \omega_L^2} \right) \left( i_{q,ref} - i_q \right) - \omega L_{mx} i_d + e_q \]  
(6)

\[ u_d = \left( k_p + \frac{k_i \omega_L}{s^2 + 2 \omega_L s + \omega_L^2} \right) \left( i_{d,ref} - i_d \right) - \omega L_{mx} i_q + e_d \]  
(7)

The controller block of three-level rectifier is shown in Fig. 2.

Controller of NP Voltage Balance

The vectors of rectifier includes six big vectors, medium vectors, small vectors and one zero vector. The space vector diagram of rectifier is shown in Fig. 3.

Figure 2. The control block diagram of T-type rectifiers under unbalanced condition.

Figure 3. Space–vector diagram of rectifiers.

For NP voltage balance, the small vectors should be used. The N-type small vector is used for increasing the bottom side dc-link voltage. The P-type small vectors are used for increasing the top side dc-link voltage. Therefore, the N-type and P-type vectors are used for balance the NP voltage.

Assuming the reference voltage is located in sector I, if \( V_{dc1} > V_{dc2} \), the dwell time of [POO] is decreased. Similarly, if \( V_{dc1} < V_{dc2} \), the dwell time of [ONN] is decreased.

Simulation of the Proposed Method

In order to verify the effectiveness of the proposed method, the rectifier system is constructed in mat lab/simulink. The simulation parameters are shown in Table I.
Table 1. Simulation Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>εa, εb, εc</td>
<td>220V, 180V, 200V</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>10k</td>
</tr>
<tr>
<td>Ts</td>
<td>100µs</td>
</tr>
<tr>
<td>Reference current</td>
<td>30A</td>
</tr>
<tr>
<td>filter</td>
<td>3.2mH</td>
</tr>
</tbody>
</table>

Fig. 4 shows the simulation results in unbalanced grid voltage condition. The parameters of grid voltages are u_a=200V, u_b=220V, u_c=190V. As shown in Fig. 4, the THD of current is high using conventional PI controller. In Fig. 5, the currents are controlled by the PIR controller, the THD is decreased.

Fig. 6 shows the line-to-line voltage and capacitor voltages. It can be seen that the top voltage and bottom voltage are balanced using the proposed method.
Summary

This paper proposes a control method for Three-level rectifier under unbalanced grid conditions. Firstly, an average model is established to analyze the influence of the unbalanced factor. The unbalanced factor will generate the negative-sequence current. And the negative-sequence current can be suppressed by a PIR controller. Moreover, the unbalance of neutral-point (NP) voltage will generate in the three-level rectifier. Therefore, this paper proposes a space vector modulation for balancing the NP voltage. Lastly, the simulation results confirm the performance and effectiveness.

References


