Research on Hysteresis-band Current Tracking Strategy for Modular Multilevel Converter in DG System

Yu Ji, Jun Mei, Xiaozhou Du, Tian Ma, Jianyong Zheng
Department of Electrical Engineering, Southeast University, NanJing, 210096, China

Abstract—Modular multilevel converter (MMC) can be used in DG system. The double closed-loop control strategy including dc bus voltage outer loop and current inner loop is adopted in the control system, which makes dc bus voltage stable even when active power changes. The current inner loop has a new control strategy which is hysteresis-band current tracking control. By real-time monitoring the voltage of the grid and the deviation between the output current and the given current, the input submodules’ number of upper/lower arm is determined. Monitoring the direction of current in one arm and comparing the voltage of submodules, then changing the working states of real submodules, the voltages of the upper/lower arm’s capacitors can be well balanced. The validity of the proposed method is verified by simulation and experimental results of five-level prototype of MMC.

Keywords—Modular multilevel converter (MMC); DG system; DC bus voltage; Hysteresis-band current tracking control; Voltage balancing control.

I. INTRODUCTION
In recent years, besides the conventional energy sources, the small scale distributed generation of power from renewable energy sources has drawn plenty of attention. Distributed Energy Resources need additional infrastructure and inverter to connect them to the grid. Modular multilevel converter (MMC) which was proposed by Marquardt and Lesnicar in Germany has attracted many researchers recently. MMC is composed of several submodules and has a common dc bus which has advantage in HVDC system and distributed generation. The output power of distributed generation is not very stable because of the fluctuation and intermittent output. The double closed-loop control strategy is based on dc bus voltage outer loop and currents inner loop. DC bus voltage is stable when the active power changes. The currents inner loop has a new control strategy which is hysteresis-band current tracking control. The proposed control strategy is simple and reliable. The validity of the proposed method is verified by the simulation results and experimental results of five-level prototype of MMC.

II. SYSTEM STRUCTURE
Fig. 1 shows the structure of DG system. Photovoltaic/fuel power system and wind power system can operate in parallel where the converter must be MMC.

![Figure 1. Structure of DG system](image)

![Figure 2. Three-phase equivalent circuit of MMC](image)

The working states of SM are shown in Table I. The output voltage of SM is “Uc” or “0” according to the current SM direction and the status of two switches. The capacitance of SM has three status. For example, if ISM >0, the capacitor would be charged, and if ISM <0, the capacitor would be discharged. The capacitor voltage will be kept while the SM is “OFF.”

<table>
<thead>
<tr>
<th>mode</th>
<th>S1</th>
<th>S2</th>
<th>ISM</th>
<th>USM</th>
<th>capacitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>&gt;0</td>
<td>UC</td>
<td>charging</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>&lt;0</td>
<td>UC</td>
<td>discharging</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>&gt;0</td>
<td>0</td>
<td>bypass</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1</td>
<td>&lt;0</td>
<td>0</td>
<td>bypass</td>
</tr>
</tbody>
</table>

B. BASIC STRUCTURE AND CONTROL
From Fig.2, output current i and output power P can be expressed as following (i=a,b,c):
\[ P_j = i_j \cdot e_j \]
\[ P_k = i_k \cdot e_k \]
\[ P_l = i_l \cdot e_l \] (1)

\( I_j \) represents the current of \( j \) phase, \( e_j \) represents the voltage of \( j \) phase, \( P_j \) represents the power of \( j \) phase.

Using Park transformation to (1), we obtain:
\[ P = e_d I_d = U_{dc} I_{dc} \]
\[ Q = -e_q I_q \] (2)

\( P \) represents the total active power, while \( Q \) represents the total reactive power. So, we obtain the double closed-loop control strategy based on dc bus voltage outer loop and currents inner loop which is seen in Fig.3. In comparison with the traditional PI control strategy, the new strategy is simple and reliable.

![Figure 3. The grid-connected Strategy of hysteresis-band current tracking control](image)

IV. \( N+1 \) HYSTERESIS-BAND CURRENT TRACKING LEVEL STRATEGY

The system is symmetrical. Just taking a phase as an example, the upper and lower arm’s voltage can be expressed as followings:
\[ \frac{U_{dc}}{2} - U_{a0} = U_{ap} + L \frac{di_{ap}}{dt} \] (3)
\[ \frac{U_{dc}}{2} + U_{a0} = U_{an} + L \frac{di_{an}}{dt} \] (4)
\[ i_{ap} = i_{an} + i_a \] (5)
\[ U_{a0} = L_a \frac{di_a}{dt} + e_a \] (6)

From (3)-(6), we obtain:
\[ L_a = L_s + \frac{L}{2} \]
\[ U_{dao} = \frac{1}{2}(U_{an} - U_{ap}) \] (7)

\( L_a \) is equivalent inductance, \( U_{dao} \) is equivalent output voltage, \( e_a \) is the voltage of grid/load. \( U_{A0} \) is the deviation between \( e_a \) and \( U_{dao} \).

![Figure 4. Principle drawing of hysteresis-band current tracking control](image)

If \( U_{A0}<0 \), the output current \( I_a \) decreases. If \( U_{A0}>0 \), \( I_a \) increases. Fig.4 shows the principle drawing of hysteresis-band current tracking control.

![Figure 5. The intervals of load voltage](image)

The intervals of the load/grid voltage is seen in Fig.5. From Fig5, we can see that there is \( n+1 \) intervals of load voltage. In order to suppress circulating-current, we adopt \( n+1 \) level strategy, then \( U_{dao} \) and SM voltage \( U_{sm} \) can be expressed as followings:
\[ U_{sm} = \frac{U_{dc}}{n} \]
\[ U_{dao}(t) = \left[ N_s(t) - 0.5n \right] \cdot U_{sm} \] (8)

\( N_s(t) \) is the sum of the input lower SM. From Fig4 and Fig5, we ensure that if \( D(t)=1 \), \( U_{dao}(t)>e_a(t) \). If \( D(t)=0 \), \( U_{dao}(t)<e_a(t) \). So, we can obtain the \( N_s(t) \) and the sum of the input upper SM \( N_p(t) \):
\[ \begin{align*}
N_s(t) &= \begin{cases} 
0 & 2D(t)+V(t)-2=-1 \\
2D(t)+V(t)-2 & 0 \leq 2D(t)+V(t)-2 \leq n \\
2D(t)+V(t)-2=n+1 & n
\end{cases} \\
N_p(t) &= n - N_s(t)
\end{align*} \] (9)

In summary, The current inner loop has a new control strategy which is hysteresis-band current tracking control. By real-time monitoring the voltage of
the grid and the deviation between the output current and the given current, the input SM number of upper/lower arm is determined, then the output current can track the given current quickly and stably.

V. CAPACITOR VOLTAGE BALANCE CONTROL

From Tab.1, there are three modes of submodule capacitor working states: "charging", "discharging" and "bypass", which is due to the arm current direction and the status of the two switches. Capacitor voltage balance is very important in MMC. We can obtain the strategy of voltage balance control: Monitoring the direction of current in one arm and comparing the voltages of submodules, then changing the working states of real submodules, the voltages of the upper/lower arm’s capacitors can be well balanced.

Assume that n is equal to 4, we can see there are 4 submodules in the upper/lower arm. If we find \( U_1 > U_2 > U_3 > U_4 \), the mapping relationships must be changed.

<table>
<thead>
<tr>
<th>TABLE II. THE WORKING STATES OF SUBMODULE</th>
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<tbody>
<tr>
<td>mode</td>
</tr>
<tr>
<td>( N_p(t)/N_n(t) )</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

Tab.2 shows the working states of submodule, we can obtain that: SM1 is the easiest discharging submodule and the hardest charging submodule while SM4 is the hardest discharging submodule and the easiest charging submodule. Therefore, the voltage of SM1 will decrease while the voltage of SM4 will increase. After several cycles, capacitor voltage balance will come true.

VI. SIMULATION AND EXPERIMENT

A. Simulation

In order to verify the validity of the analyses, we build simulation model in matlab/simulink. The simulation parameters are seen in Tab.3. The simulation waveforms are seen in Fig.6.

<table>
<thead>
<tr>
<th>TABLE III. THE SIMULATION PARAMETERS</th>
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<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>No.of Submodules in each arm</td>
</tr>
<tr>
<td>Submodule Capacitor C</td>
</tr>
<tr>
<td>Arm Equivalent Resistance</td>
</tr>
<tr>
<td>Arm Inductor L</td>
</tr>
<tr>
<td>AC Link Inductor L&lt;sub&gt;s&lt;/sub&gt;</td>
</tr>
<tr>
<td>DC Bus Voltage U&lt;sub&gt;dc&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

Figure 6. The simulation waveforms of hysteresis-band current tracking control

From Fig6(a), We can see the change of absorbing and producing active power. The absorbing active power increases from 18kW to 27kW, then the producing active power will increase accordingly. Fig6(b) shows the output current of three-phases. The current increases quickly after 0.2s which is symmetrical. Fig6(c) shows the grid voltage, output voltage and output current of a single phase. We can
find that the output current can track the given current smoothly. Fig6(d) shows the voltages of SMs, the voltages of the upper/lower arm’s capacitors can be well balanced.

**B. Experiment**

The experimental parameters are the same as Tab.3, waveforms are shown in Fig.7.

![Figure 7. Experimental waveforms](image)

Fig7(a) shows the output current and output voltage, we can see that they have the same phase, the voltage of the dc bus is 800V which is stable. Fig7(b) shows the voltages of SMs, the voltages of the upper/lower arm’s capacitors can be well balanced.

**VII. CONCLUSIONS**

In this paper, Hysteresis-band Current Tracking Strategy for modular multilevel converter in distributed generation is introduced. The output current can track the given current smoothly and the voltages of the upper/lower arm’s capacitors can be well balanced. The proposed strategy is simple and reliable for control which has great promise.

**REFERENCES**


