Low voltage ride-through control strategy based on cascaded H-bridge that can avoid overmodulation and power backflow

Menglong Zhou*, Fusheng Wang

Electrical and Automation Engineering Department, Hefei University of Technology, Hefei City, Anhui Province, 230000, China

*Corresponding author’s e-mail: 2019170363@mail.hfut.edu.cn

Abstract. Because of its multi-level output voltage and modular structure, the cascaded H-bridge(CHB) multi-level inverter can expand the system to higher voltage and power levels. It has good development and application prospects in the photovoltaic grid-connected market. Under the power grid fault voltage sag, the system should generate reactive power according to national codes and meet the dynamic performance requirements to maintain the connection with the grid, and achieve the minimum requirements of low voltage ride through(LVRT). Aiming at the over-modulation and the unique power backflow problem of cascaded H-bridges, a LVRT control algorithm that can avoid over-modulation and power backflow is studied, and MATLAB simulation verification is carried out under common grid faults, which proves the correctness of the theory.

1. Introduction

The multi-level inverter structure reduces the stress of each switching device by increasing the number of switching devices. Combined with the advantages of small output voltage change rate, high system efficiency and small filter size, in the future, photovoltaic inverters will develop in the direction of higher level numbers. The multi-level inverter topology has a large number of output levels, which is beneficial to improve the harmonic content of the grid current, and can achieve higher voltage and lower harmonic requirements. Compared with the diode clamp type and the flying capacitor type flat topology structure, when the CHB inverter outputs the same number of levels, it uses the least components and has a modular structure, the layout is also the simplest, easy to expand, and the cost is low. The DC side of each H-bridge can be powered by an independent DC source, which can realize multi-channel maximum power point tracking(MPPT) to improve power generation and power generation efficiency. Therefore, the CHB structure is considered to be the most suitable topology for next-generation photovoltaic inverters and has been widely used in photovoltaic power generation systems.

As the installed capacity of photovoltaic inverters continues to increase, when the grid fails and the point of common coupling drops, in order to effectively support the restoration of the grid voltage, various countries have formulated relevant standards one after another, and it have rigid requirements for photovoltaic power plants. It is required that the photovoltaic system connected to the grid can work stably in a specific time interval and voltage sag area without going off the grid, that is to say, it has low voltage ride-through capability.

The most basic and most important goal of LVRT is to meet the requirements of reactive current and dynamic performance required by national standards during the voltage sag. In addition, there is also the maximum active power to be issued and eliminate the active power of double frequency.
fluctuations and other control targets during the sag. Over-modulation will cause the grid current to be distorted, and the power backflow will cause the DC bus voltage to continue to rise. When the upper limit of the voltage is exceeded, the protection mechanism will be triggered to disconnect from the grid. For over-modulation and the power backflow problem of unique CHB, the article proposes a LVRT control algorithm that can avoid over-modulation and power backflow. When over-modulation or power backflow occurs, the current reference value can be changed by the algorithm to effectively avoid over-modulation or power backflow.

2. LVRT control principle

2.1. System topology

The system topology based on the CHB is shown in Figure 1. The DC source is LLC input equal to 360V, LLC output is controlled to 17V, one LLC is connected to one module, and one module contains 4 H-bridge cascades, that is "one drives four" structure. The AC side is connected to a 4.2mH filter inductor and then to the grid, the effective value of the grid phase voltage is 38V.

![System topology diagram based on CHB.](image)

2.2. Over-modulation

The positive- and negative-sequence voltage of αβ-frame \( v_a^+ , v_a^- \) and \( v_b^+ , v_b^- \) is

\[
\begin{align*}
v_a^+ &= V^+ \cos(\omega t + \varphi^+) \\
v_a^- &= V^- \cos(-\omega t - \varphi^-) \\
v_b^+ &= V^+ \sin(\omega t + \varphi^+) \\
v_b^- &= V^- \sin(-\omega t - \varphi^-)
\end{align*}
\]

where \( V^+ \) and \( V^- \) are the sequence amplitude, \( \omega \) is the grid angular frequency, and \( \varphi^+ \) is the phase angle of positive, \( \varphi^- \) the phase angle of negative, \( \varphi = \varphi^+ - \varphi^- \)

\( \varphi \) can be obtained by DDSRF-PLL, positive- and negative-sequence voltage of dq-frame is

\[
\begin{align*}
v_d^+ &= V^+ \\
v_d^- &= V^- \cos \varphi \\
v_q^+ &= 0 \\
v_q^- &= V^- \sin \varphi
\end{align*}
\]

The voltage unbalance factor \( n \) can be mathematically defined as the ratio of the \( V^- \) to the \( V^+ \)
3

\[ n = \frac{V^+}{V^-} \]  \hspace{1cm} (3)

The equation can be listed by Figure 1

\[ N \cdot U_{dc} \cdot d_\alpha = L_g \frac{di_\alpha}{dt} + v_\alpha \]  \hspace{1cm} (4)

\[ N \cdot U_{dc} \cdot d_\beta = L_g \frac{di_\beta}{dt} + v_\beta \]

where \( N \) is the number of cascaded H-bridge modules, \( U_{dc} \) is the DC side voltage of the H-bridge, \( d_\alpha \) and \( d_\beta \) is \( \alpha\beta \)-frame the duty cycle of the modulation wave, \( L_g \) is the filter inductance, \( v_\alpha \) and \( v_\beta \) are the \( \alpha\beta \)-frame components, \( i_\alpha \) and \( i_\beta \) are the \( \alpha\beta \)-frame components.

To prevent over-modulation, necessary is

\[ d_{\alpha,\beta,\gamma} \leq 1 \]  \hspace{1cm} (6)

(5) substituting into (4) and applying the inverse Clarke’s transformation, and then combining (6) to obtain

\[ a \left(I_p^+\right)^2 + bI_p^+ + c\left(I_q^+\right)^2 + dI_q^+ + e + f \leq 0 \]

\[ \Rightarrow OM_\alpha - I_p^+ \leq \frac{-b + \sqrt{b^2 - 4a \left[cI_q^+ + dI_q^+ + e + f\right]}}{2a} \]  \hspace{1cm} (7)

when \( I_p^+ = nI_p^+, I_q^- = nI_q^+ \), (7) is

\[ a = \omega^2 L_g \left[1 + n^2 - 2nw\right] \quad b = -4\omega L_g V^- z \quad c = a \]

\[ d = 2\omega L_g \left(V^+ - nV^-\right) \quad e = \left(V^+\right)^2 + \left(V^-\right)^2 + 2V^+V^- w \quad f = -N^2 U_{dc}^2 \]  \hspace{1cm} (8)

when \( V^+ = V^- \), (7) is

\[ a = \omega^2 L_g^2 \quad b = -2\omega L_g V^+ z \quad c = a \]

\[ d = 2\omega L_g V^+ \left(1 + w\right) \quad e = 2 \left(1 + w\right) \left(V^+\right)^2 \quad f = -N^2 U_{dc}^2 \]  \hspace{1cm} (9)

where

A phase, \( w = \cos \varphi, \quad z = \sin \varphi \)

B phase, \( w = \cos(\varphi + 120^\circ), \quad z = \sin(\varphi + 120^\circ) \)

C phase, \( w = \cos(\varphi - 120^\circ), \quad z = \sin(\varphi - 120^\circ) \)

2.3. Power backflow

The formula for obtaining the active power is\[4\]
\[ P = \frac{1}{2\pi} \int_0^{2\pi} V \cdot idt \] (10)

(1) and (5) applying the inverse Clarke’s transformation and substituting (10)

\[
P_A = \frac{1}{2} V^+ I_p^+ + \frac{1}{2} \left( V^- I_p^- - V^+ I^+_p \right) \cos \varphi + \frac{1}{2} \left( V^- I_q^- + V^+ I^+_q \right) \sin \varphi - \frac{1}{2} V^- I_p^-
\]

\[
P_B = \frac{1}{2} V^+ I_p^+ + \frac{1}{2} \left( V^- I_p^- - V^+ I^+_p \right) \cos(\varphi + 120^\circ) + \frac{1}{2} \left( V^- I_q^- + V^+ I^+_q \right) \sin(\varphi + 120^\circ) - \frac{1}{2} V^- I_p^-
\]

\[
P_C = \frac{1}{2} V^+ I_p^+ + \frac{1}{2} \left( V^- I_p^- - V^+ I^+_p \right) \cos(\varphi - 120^\circ) + \frac{1}{2} \left( V^- I_q^- + V^+ I^+_q \right) \sin(\varphi - 120^\circ) - \frac{1}{2} V^- I_p^-
\]

when \( I_p^+ = n I_p^+, I_p^- = n I_p^- \), (11) is

\[
P_A = \frac{1}{2} V^+ I_p^+ + V^- I_q^+ \sin \varphi - \frac{1}{2} V^- I_p^-
\]

\[
P_B = \frac{1}{2} V^+ I_p^+ + V^- I_q^+ \sin(\varphi + 120^\circ) - \frac{1}{2} V^- I_p^-
\]

\[
P_C = \frac{1}{2} V^+ I_p^+ + V^- I_q^+ \sin(\varphi - 120^\circ) - \frac{1}{2} V^- I_p^-
\]

Make \( P_{dth,min} \geq 0 \), have

\[
PR_{I_p^{max}} = \frac{-2ny}{1-n^2} I_q^+
\]

where

\[
y = \min \{ \sin \varphi, \sin(\varphi + 120^\circ), \sin(\varphi - 120^\circ) \}
\]

when \( V^+ = V^- \), (11) is

\[
PR_{I_p^{max}} = \sqrt{3} I_q^+
\]

3. Simulation result

The above derivation is verified with MATLAB/Simulink. The cascaded H-bridge is 4 H-bridges cascaded per phase, the simulation parameters are shown in Table 1.

| Quantity          | Symbol | Nominal value |
|-------------------|--------|---------------|
| dc-link voltage   | Udc    | 360V          |
| inverter inductance | Lg   | 4.2mH         |
| grid voltage      | v      | 53.74V(1-n,peak) |
| control frequency | f_s    | 10kHz         |
| carrier frequency | f_c    | 500Hz         |

3.1. Over-modulation simulation result

Figure 2 shows short circuit between phase B and phase C and D=0.3(D indicates the ratio of the line voltage amplitude of the short-circuited two phases before and after sag) without adding the over-modulation algorithm waveform chart. Short circuit between phase B and phase C and D=0.3 sag occurs when 0.3s, and it recovers in 0.6s, PN = 2500W, and the active power command Pref = 500W, this moment over-modulation critical value calculation formula is equation (8), Figure 2(a) is the three-phase over-modulation critical value and the actual positive-sequence active current waveform, you can see \( I_p^+ > OM_{-I_p^{max}} \cdot C \), \( I_p^+ < OM_{-I_p^{max}} \cdot A \) and \( I_p^+ < OM_{-I_p^{max}} \cdot B \), so phase C will be over-modulated, phase A and phase B will not be over-modulated. Figure 2(b) is the three-phase modulation waveform. It can be clearly seen that phase C is over-modulated, phase A and phase B do
not occur over-modulation, Figure 3 shows short circuit between phase B and phase C and D=0.3 with the over-modulation algorithm waveform. When over-modulation occurs, making 
\[ I_p^* = OM \_ I_{p max}^* \]. From Figure 3(a), we can see that 
\[ I_p^* = OM \_ I_{p max}^* = OM \_ I_{p max}^* \_ C \], 
\[ I_p^* < OM \_ I_{p max}^* \_ A \] and \[ I_p^* < OM \_ I_{p max}^* \_ B \], now look at the three-phase modulation waveform in Figure 3(b), you can see that phase C is just in the critical state of over-modulation, phase A and phase B do not over-modulate, verifying the theoretical formula of over-modulation (8) is correct.

Figure 2. Short circuit between phase B and phase C and D=0.3 without over-modulation algorithm. (a) three-phase over-modulation critical value and positive-sequence active current. (b) three-phase modulation waveform.

Figure 3. Short circuit between phase B and phase C and D=0.3 with over-modulation algorithm. (a) three-phase over-modulation critical value and positive-sequence active current. (b) three-phase modulation waveform.

Figure 4 is short circuit between phase B and phase C and D=0 without adding the over-modulation algorithm. Short circuit between phase B and phase C and D=0 sag occurs when 0.3s, and it recovers in 0.6s, PN = 1600W, and the active power command Pref = 1000W, this moment over-modulation critical value calculation formula is equation (9), making 
\[ I_p^* = 20 \], at this moment 
\[ \max_{pp} IO M I A \] \[ \max_{pp} IO M I B \] and \[ \max_{pp} IO M I C \] as shown in Figure 4(a). So phase A over-modulation will occur, B-phase and C-phase will not be over-modulated, as shown in Figure 4(b). Figure 5 is short circuit between phase B and phase C and D=0 with the over-modulation algorithm, let 
\[ I_p^* = OM \_ I_{p max}^* \], we can see from Figure 4(a), 
\[ I_p^* = OM \_ I_{p max}^* = OM \_ I_{p max}^* \_ A \],
$I_p < OM_{\text{max}} B$ and $I_p < OM_{\text{max}} C$, then look at figure 5(b) three-phase modulation waveform, it can be seen that phase A is just in the critical state of over-modulation, and phase B and phase C do not over-modulate, which verifies the correctness of the over-modulation theory formula (9).

Figure 4. Short circuit between phase B and phase C and D=0 without over-modulation algorithm. (a) three-phase over-modulation critical value and positive-sequence active current. (b) three-phase modulation waveform.

Figure 5. Short circuit between phase B and phase C and D=0 with over-modulation algorithm. (a) three-phase over-modulation critical value and positive-sequence active current. (b) three-phase modulation waveform.

3.2. Power backflow simulation result

Figure 6 is short circuit between phase A and grounding and D = 0.3(D indicates the ratio of the phase voltage amplitude of the short-circuited phases before and after sag) without the power backflow algorithm. Short circuit between phase A and grounding and D=0.3 sag occurs when 0.3s, and it recovers in 0.6s, PN = 2500W, and the active power command Pref = 500W. The calculation formula of the critical value $PR_{\text{min}}$ for the power backflow at this moment is equation (13). It can be seen from Figure 6(a) that $I_p < PR_{\text{min}}$ during the stable period after sag, so power backflow will occur. Figure 6(b) is the three-phase DC side active power, $PA = 163.1W > 0$, $PB = -55.03W < 0$, $PC = 433.1W > 0$, and phase B has power backflow. Figure 7 is short circuit between phase A and grounding and D = 0.3 with the power backflow algorithm. When the power backflow occurs, making $I_p = PR_{\text{min}}$, Figure 7(a) is the three-phase DC side active power waveform with the power backflow algorithm. The active power emitted by the three-phase DC side is $PA = 223.6W > 0$, $PB = 24.01W > 0$, and $PC = 512.8W > 0$. Considering some errors in the calculation and device losses, the
active power emitted by the phase B DC side is close to 0. Verifying when $I_p^+ \geq PR_{-I_p^{\min}}$, the minimum phase active power from the three-phase DC side is also greater than or equal to 0.

Figure 6. Short circuit between phase A and grounding and $D=0.3$ without power backflow algorithm. (a) power backflow critical value and positive-sequence active current. (b) three-phase DC side power.

Figure 7. Short circuit between phase A and grounding and $D=0.3$ with power backflow algorithm. (a) power backflow critical value and positive-sequence active current. (b) three-phase DC side power.
Figure 8. Short circuit between phase B and phase C and D=0 without power backflow algorithm. (a) power backflow critical value and positive-sequence active current. (b) three-phase DC side power.

Figure 8 is short circuit between phase B and phase C and D=0 without the power backflow algorithm. Short circuit between phase B and phase C and D=0 sag occurs when 0.3s, and it recovers in 0.6s, PN = 2500W, and the active power command Pref = 500W. The calculation formula of the critical value $PR_\text{min}$ for the power backflow at this moment is equation (15), that is $PR_\text{min} = \sqrt{3}I_1R$. From Figure 8(a), it can be seen that $I_1 < PR_\text{min}$ during the stable period after sag, so power backflow will occur. Figure 8(b) is the active power of DC side is PA = 382.5W> 0, PB = 302.1W> 0, PC = -82.95W <0, and phase C occur power backflow. Figure 9 is short circuit between phase B and phase C and D=0 with the power backflow algorithm. Figure 9 (a) is the active power of DC side is PA = 728.3W> 0, PB = 433.6W> 0, PC = -11.08 <0. Considering some errors in the calculation and device loss, the active power of phase C of DC side is close to 0, verifies that when $I_1 \geq PR_\text{min}$, the minimum active power of DC side is great then or equal to 0.
4. Conclusion
Over-modulation will cause the current distort, and the unique power backflow of CHB will cause the DC bus voltage to continue to rise. For the two questions, this paper studies a LVRT control algorithm that avoids over-modulation and power backflow, and derives the critical current command value for over-modulation and power backflow. If over-modulation and power backflow occur, without sacrificing compliance with national standards, making $I_p^{OM} = I_{p_{max}}^{OM}$ or $PR \_I_{p_{min}}$ to avoid over-modulation and power backflow. Finally, the above algorithm derivation is verified by MATLAB. The dynamic performance of LVRT has always been a difficult and important point, we need to focus on it.

References
[1] Zhao T, Zhang X. (2017) A control strategy of cascaded H-bridge photovoltaic grid-connected inverter. Power Electronics, 51(12):84-86.
[2] M. A. Garnica López, J. L. García de Vicuña, J. Miret, M. Castilla and R. Guzmán(2018), Control Strategy for Grid-Connected Three-Phase Inverters During Voltage Sags to Meet Grid Codes and to Maximize Power Delivery Capability, IEEE Transactions on Power Electronics, vol. 33, no. 11, pp. 9360-9374.
[3] A. Camacho, M. Castilla, J. Miret, L. G. de Vicuña and R. Guzman(2017), Positive and Negative Sequence Control Strategies to Maximize the Voltage Support in Resistive–Inductive Grids During Grid Faults, IEEE Transactions on Power Electronics, vol. 33, no. 6, pp. 5362-5373.
[4] Zhao T.(2020) Research on key technology of photovoltaic grid-connected inverter based on cascaded H-bridge topology and its application. In: Hefei University of Technology.