An Additional DC Voltage Control Strategy for Modular Multilevel Converter

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Abstract. This paper proposed an additional DC voltage controller to adjust the DC voltage to keep the modulation index of a converter within a proper range. Firstly, through the modulation theory of modular multilevel converter, it illustrates the minimum value of modulation index which is critical to guarantee the converter to generate staircase waveform with full voltage levels. Secondly modulation index should be lower than 1 to keep the converter stable operation. Therefore, the additional control strategy and its controller are introduced to realize a dynamic control of DC voltage which has a non-linear relationship with the modulation index. In addition, the calculation method of upper and lower limits for the output of the proposed controller is essential to maintain a proper modulation index for each converter, especially in a multi-terminal system. Simulation results show the proposed control strategy is effective and the controller can achieve the goals.

Introduction

Since the advent of power electronic switch devices such as gate turn off (GTO) thyristors and insulated-gate bipolar transistors (IGBTs), voltage source converter (VSC) [1],[2] has presented many merits compared with the conventional high-voltage direct-current (HVDC) converter [3],[4]. With the help of GTO thyristors or IGBTs, VSC will not occur commutation failure which is a common problem in conventional HVDC inverters [5],[6]. Another benefit is that VSC features the independent control of active and reactive power, which allows the converters transmit large amount of active power while not consuming any reactive power [7].

However, two or three voltage levels VSC has three main drawbacks, that is, large power losses caused by high switching frequency of the switch devices [8], high percentages of harmonic components due to a low voltage level number in the output alternative current (AC) voltage [9], and the demand of absolute operation consistency of the IGBTs in series [10]. To overcome these disadvantages, a new topology of VSC, called modular multilevel converter (MMC), is firstly introduced in [11].

The number of inserted submodules in each arm of MMC is determined by sinusoidal pulse widen modulation (SPWM) [12]-[13]. However, a low modulation index (m) will lead to a loss of voltage levels in AC output voltage of the converter. On the other hand, when the modulation index is greater than 1 and lasts for a while, the operation state of the converter will be unstable. So firstly $m_{\text{min}}$, the minimum value of modulation index to keep the output AC voltage with $N+1$ voltage levels, is computed in this paper, and then an additional DC voltage control strategy is proposed to make sure that $m$ is within the range between $m_{\text{min}}$ and 1. Thus, the converter is able to operate stably and generate AC voltage with absolute $N+1$ voltage levels.
The Proper Range of Modulation Index

The Value of $m_{\text{min}}$

In SPWM method, for a MMC with $N$ submodules in an arm (ignoring the redundant ones), the carrier waves separate the magnitude axis into $N$ sections with a same length. To realize this function, for instance, phase disposition-SPWM (PD-SPWM) \cite{12} method utilizes $N$ in-phase carrier waveforms displaced symmetrically with respect to the zero-axis, while carrier phase shifted-SPWM (CPS-SPWM) \cite{13} adopts the crossing points of all carrier waveforms. An example for each modulation method is shown in Figure 1(a)-(b), respectively. The equivalent $N$ sections and two sinusoidal modulation waveforms with different magnitudes are indicated in Figure 1(c). When the modulation waveforms are varying within a certain section, detail PWM process is equivalent as Figure 1(d) according to a same duty cycle. Staircase wave 1 and staircase wave 2 in Figure 1(d) are generated by modulation wave 1 and modulation wave 2 in Figure 1(c) individually.

From Figure 1, the magnitude of modulation wave 2 cannot reach the top section and the bottom section. As a result, staircase wave 2 loses two voltage levels which are the highest and lowest voltage level. Therefore, according to the modulation method in \cite{12} and \cite{13}, the number of inserted submodules in an arm is impossible to be 0 or $N$. Therefore, the output AC voltage of the converter is unable to get the full number of voltage levels.

For solving the aforementioned problem, the minimum magnitude of the modulation wave is,

$$M_{\text{mod-min}} = M_{\text{car}} - \frac{M_{\text{car}} - (-M_{\text{car}})}{N}$$  \hspace{1cm} (1)

where $M_{\text{car}}$ is the peak value of the top section formed by the carriers in Figure 1. Rewriting (1), the minimum modulation index to ensure the full voltage levels is,

$$m_{\text{min}} = \frac{M_{\text{mod-min}}}{M_{\text{car}}} = \frac{N - 2}{N}$$  \hspace{1cm} (2)

It can be seen from (2) that $m_{\text{min}}$ is closer to 1 with the increase of $N$. Therefore, for an MMC with a large number of submodules in an arm, the modulation index should be closer to 1 to ensure the output AC voltage of the converter is of full voltage levels. Otherwise, it causes a loss of voltage levels and higher total harmonic distortion (THD).

The Stable Dynamics of MMCs

The steady state characteristics of MMC are same with the conventional VSCs \cite{14}. Define $U_S$ and $U_C$ as the line to line root mean square voltages of the AC system and the AC output voltage of the
converter, $\delta$ is the angle that $U_C$ lags $U_S$. The active and reactive power ($P$ and $Q$) from the AC system to the converter are calculated as,

$$
\begin{align*}
P &= \frac{U_S U_C \sin \delta}{X_L} \\
Q &= \frac{U_S(U_L - U_C \cos \delta)}{X_L}
\end{align*}
$$

(3)

where $X_L$ is the reactance between the AC system and the converter. Reform (3) into (4),

$$
P^2 + Q^2 = \left(\frac{U_S U_C}{X_L}\right)^2\sin^2 \delta
$$

(4)

The relationship between $U_C$ and $U_{dc}$ is,

$$
U_C = \frac{km}{\sqrt{2}} U_{\omega}
$$

(5)

where $k$ is the DC voltage utilization index. For SPWM method, $k$ is approximately equal to 0.866. Combining (4) and (5), we have,

$$
P^2 + Q^2 = \left(\frac{km U_S}{\sqrt{2} X_L}\right)^2
$$

(6)

Usually $m$ is in the range between 0 and 1 [15], and the limitation circle of the converter is shown in Figure 2. MMC can stably operate within the circle. When $m$ is 1, $(P, Q)$ is in the boundary, which means the converter is operating in a critical state. If $(P, Q)$ is out of the limitation circle, there is $m>1$ and the converter will be unstable. Therefore, the additional DC voltage controller proposed in this paper should guarantee that $m$ is always within the range $[m_{\text{min}}, 1]$ for different points of $(P, Q)$.

![Figure 2. The limitation circle of converter.](image)

The Additional DC Voltage Control Strategy

The Basic Theory of the Proposed Strategy

As (3) indicates, $U_C$ can be determined by a certain point $(P, Q)$. And (5) shows that $m$ can be controlled by $U_{dc}$ when $U_C$ is fixed. Based on these two ideas, the proposed control strategy diagram can be reflected by Figure 3. $u_{abc}$ is the three-phase sinusoidal voltage out of the converter. $U_C$ can be obtained from $u_{abc}$ through a fast Fourier transform (FFT) block. Then the modulation index $m$ can be obtained by (5). The additional DC voltage controller utilizes the modulation index $m$ to generate $\Delta U_{dc}$ which can adjust the DC voltage reference value $U_{dc_{\text{ref}}}$. By a d-q decoupled controller, the DC voltage $U_{dc}$ can be controlled with the change of $i_{d_{\text{ref}}}$ (the current reference value of d-axis). A lag function $G_1/(1+sT_1)$ is used to measure $U_{dc}$. For an MMC-HVDC system, however, it is necessary to ensure that the modulation indexes for all converters are within the range $[m_{\text{min}}, 1]$. Therefore, both an
upper limit and a lower limit are needed for $\Delta U_{dc}$ to guarantee all modulation indexes are in a proper range.

Figure 3. The additional DC voltage control strategy.

The Upper and Lower Limits of $\Delta U_{dc}$

According to (6), the relationship among $m$, $U_{dc}$, and $(P, Q)$ is

$$
\begin{align*}
    m &= \frac{W_P}{U_{dc}} \\
    W_P &= \sqrt{2\sqrt{P^2 + (Q - U_{dc}^2 / X_l)^2}} / kU_s
\end{align*}
$$

(7)

Obviously in (7) that $m$ and $U_{dc}$ have an inversely proportional relationship. And the key parameter $W_P$ is determined by $P$ and $Q$. For a multi-terminal MMC-HVDC system, it only demands that the sum of active power from the rectifier converters is equal to the total active power released by the inverters. So both $P$ and $Q$ in each converter can make contributions to different values of $W_P$. However, for a two terminal MMC-HVDC system, the absolute values of active power absorbed from the rectifier and released by the other side converter are same. So only different $Q$ in each converter can cause the difference of $W_P$ between two converters.

Define $\Delta U_{dc\,\text{max}}$ and $\Delta U_{dc\,\text{min}}$ as the upper and lower limit of $\Delta U_{dc}$. Usually two conditions should be considered to determine the values of $\Delta U_{dc\,\text{max}}$ and $\Delta U_{dc\,\text{min}}$, that is,

a) $U_{dc} + \Delta U_{dc\,\text{max}}$ should be within the voltage tolerance of the converter. This can ensure the electric devices, especially for the IGBTs, not be broken by a much higher voltage.

b) When $U_{dc}$ is in the range $[U_{dc\,-\Delta U_{dc\,\text{min}}, U_{dc}\,+\Delta U_{dc\,\text{max}}]$, the modulation index $m$ for each converter should be located within the section $[m_{\text{min}}, 1]$. Therefore, all converters in the MMC-HVDC system can operate in steady state with full voltage levels.

To satisfy condition b), (7) is used to find out proper $\Delta U_{dc\,\text{max}}$ and $\Delta U_{dc\,\text{min}}$. A two terminal MMC-HVDC system is selected as an example to illustrate the calculation method. Assuming $W_{P1}$ and $W_{P2}$ belongs to two converters respectively and $W_{P1} > W_{P2}$. The $m$-$U_{dc}$ curves for the converters are shown in Figure 4. With $m=1$ and $m=m_{\text{min}}$, $(U_{dc\,\text{min}1}, U_{dc\,\text{min}2})$ and $(U_{dc\,\text{max}1}, U_{dc\,\text{max}2})$ can be solved. Then, with the initial DC voltage $(U_{dc\,\text{initial}})$ of the MMC-HVDC system, $\Delta U_{dc\,\text{min}}$ and $\Delta U_{dc\,\text{max}}$ can be obtained as,

$$
\begin{align*}
    \Delta U_{dc\,\text{min}} &= U_{dc\,\text{min}1} - \max(U_{dc\,\text{min}1}, U_{dc\,\text{min}2}) \\
    \Delta U_{dc\,\text{max}} &= \min(U_{dc\,\text{max}1}, U_{dc\,\text{max}2}) - U_{dc\,\text{initial}}
\end{align*}
$$

(8)

where max() and min() are the functions to obtain the maximum value and minimum value respectively.
For a multi-terminal MMC-HVDC system with $N_{con}$ converters, there are $N_{con}$ curves of $m-U_{dc}$. With $m=1$ and $m=m_{\text{min}}$, the $\Delta U_{dc_{\text{min}}}$ and $\Delta U_{dc_{\text{max}}}$ can be conveniently calculated as (9), which is similar to the process in two terminals system.

$$$
\begin{align}
\Delta U_{dc_{\text{min}}} &= U_{dc_{\text{initial}}} - \max_i (U_{dc_{\text{min}}}) \\
\Delta U_{dc_{\text{max}}} &= \min_i (\Delta U_{dc_{\text{max}}}) - U_{dc_{\text{initial}}}
\end{align}
$$$

(9)

The Additional DC Voltage Controller

As (7) indicates, different $P$ and $Q$ will lead to the variation of $m$. However, because of the ability of MMC to swiftly adjust active and reactive power [16], $P$ and $Q$ of the converter often change to realize a power support strategy which is a common event in power grid. Therefore, $m$ has a great possibility to exceed the range $[m_{\text{min}}, 1]$. To solve this problem, three main tasks should be achieved by the proposed DC voltage controller, as follows.

① In the normal operation, when $m$ is between $m_{\text{min}}$ and 1, $\Delta U_{dc}$ should be 0 and the additional DC voltage controller has no effect on the converters.

② If $m$ is smaller than $m_{\text{min}}$, $\Delta U_{dc}$ should be a negative constant as $\Delta U_{dc_{\text{neg}}}$ which will adjust $U_{dc}$ to make $m$ back to the range $[m_{\text{min}}, 1]$. However, when $m$ is back to the proper range, this situation is not same as ①. $\Delta U_{dc}$ has to maintain $\Delta U_{dc_{\text{neg}}}$ rather than 0 because $m$ will be lower than $m_{\text{min}}$ again with $\Delta U_{dc}=0$. As a result, $\Delta U_{dc}$ oscillates between 0 and $\Delta U_{dc_{\text{neg}}}$ and the MMC-HVDC system is unstable.

③ When $m$ exceeds 1, $\Delta U_{dc}$ turns out to be a positive value so that $U_{dc}$ increases and $m$ falls into the range $[m_{\text{min}}, 1]$. Similar with ②, the oscillation in $\Delta U_{dc}$ will be avoided if $\Delta U_{dc}$ could continuously keep the positive constant.

For addressing the above goals, the block of the additional DC voltage controller is shown in Fig. 5. $\Delta U_{dc_{\text{L1}}}$ and $\Delta U_{dc_{\text{L2}}}$ are generated by proportional-integral (PI) 1 and PI2 separately to limit the output of the central linear block. An enabled signal is set as $EN$ for which $EN=0$ means disabling the controller while $EN=1$ stands for an enabled controller. A lag function $G_2/(1+sT_2)$ is used to reduce the impact of sudden change of $\Delta U_{dc}$. The central linear block can be described as ($K_P>0$),

$$$
\Delta U_{dc} = \begin{cases} 
K_P (m - m_{\text{min}}) & m < m_{\text{min}} \\
0 & m_{\text{min}} \leq m \leq 1 \\
K_P (m - 1) & m > 1
\end{cases}
$$$

(10)
Simulation Tests

Simulation System

A two terminal MMC-HVDC system is shown in Fig. 6. The initial value of $U_{dc}$ is 20kV. $U_{s1}=U_{s2}=10.2kV$ and $X_L=3.14\text{ohms}$. Each arm of the converter has 10 submodules so the total voltage level number is 11. As a result, $m_{\text{min}}$ of this MMC-HVDC system is 0.8 by (2). There are three different cases set by different $(P_1, Q_1)$, which are listed in Table 1. The modulation indexes $m_1$ for MMC1 and $m_2$ for MMC2 in each case are calculated by (7).

Table 1 shows that $m_2$ of MMC2 is in the proper range $[0.8, 1]$ in case1 through case3. However, $m_1$, the modulation index of MMC1, is between 0.8 and 1 in case1, smaller than 0.8 in case2, and greater than 1 in case3. Therefore, the validation of the proposed DC voltage strategy can be performed via case1 through case3. The time sequence of these three cases is arranged as Figure 7.

Ensure Full Voltage Levels

$K_p$ in (10) is 100, $\Delta U_{dc,\text{min}}=0.3\text{(p.u.)}$, and $\Delta U_{dc,\text{max}}=0.3\text{(p.u.)}$. For a stability margin, $m_{\text{min}}$ is set as 0.81 which is a little higher than 0.8. Parameters of PI controllers and lag functions are shown in Table 2.
Table 2. Parameters of the proposed controller.

<table>
<thead>
<tr>
<th>PI</th>
<th>PI1</th>
<th>PI2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_{PI1}$</td>
<td>$T_{PI1}$/s</td>
</tr>
<tr>
<td>G/(1+sT)</td>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td>$G_1$</td>
<td>$T_1$/s</td>
<td>$G_2$</td>
</tr>
<tr>
<td>1</td>
<td>0.02</td>
<td>1</td>
</tr>
</tbody>
</table>

When the MMC-HVDC system changes from case 1 to case 2, the $EN$ signal, $\Delta U_{dc}$, $m$, staircase waveform of MMC$_1$ and its THD are shown in Fig. 8. When the system is in case 1, $m$ is greater than $m_{min}=0.81$. Therefore, the staircase waveform maintains 11 voltage levels. However, the system comes into case 2 at 4s and immediately $m$ falls to 0.78. Due to a disabled additional DC voltage controller by $EN=0$, two voltage levels are lost in the staircase waveform and THD increases. Enabling the proposed controller at 4.5s, a swift response appears in $\Delta U_{dc}$ to adjust DC voltage so that $m$ comes back to the proper range soon. Thus the staircase waveform recovers to the full voltage level state and THD reduces.

![Figure 8](image1.png)

Keep Steady Operation

Indicated by Table 1, if the MMC-HVDC system comes into case 3 without the proposed controller, $m>1$ and the system will be unstable, shown as Figure 9 where oscillations occur in $P_1$, $Q_1$ and $U_{dc}$.

However, with the additional DC voltage controller, the MMC-HVDC system can operate stably and no fluctuation appears in $P_1$, $Q_1$ and $U_{dc}$. As shown in Figure 10, the reason is that the proposed controller produces a positive $\Delta U_{dc}$ to promote the DC voltage once $m>1$ is found. Consequently the modulation index reduces to a proper value to keep the system stable operation. By using the $\Delta U_{dc_{\min}}$ and $\Delta U_{dc_{\max}}$ determined by (10), $m_1$ and $m_2$ are always adjusted to the range [0.81, 1], which also ensures the entire DC system a well performance.

![Figure 9](image2.png)
Conclusions

This paper is concentrated on the effect of modulation index on keeping MMC-HVDC system stable operation with full voltage levels. And an additional DC voltage controller is presented to adjust DC voltage and keep the modulation index of each converter within a proper range. With the proposed control strategy, the entire DC system is able to find a new steady operation point facing up to various active and reactive power of the converters. The main achievements of this paper are listed as follows.

1) A calculation method is proposed to determine the proper range \([m_{\text{min}}, 1]\) for modulation index of a converter. When the modulation index is lower than \(m_{\text{min}}\), the converter cannot generate AC voltage with full voltage levels. On the other hand when \(m>1\), the converter will be unstable.

2) It illustrates the relationship between DC voltage and modulation index to design an additional DC voltage controller. The non-linear part of \(U_{\text{dc}} \sim m\) in (7) is controlled by two PI controllers which perform well dynamic behaviors.

3) The method to obtain \(\Delta U_{\text{dc,min}}\) and \(\Delta U_{\text{dc,max}}\) is critical to guarantee that all converters in the multi-terminal MMC-HVDC system can have a proper modulation index in the range \([m_{\text{min}}, 1]\). Therefore, the entire DC system can always reach a new steady operation state when the operation point changes.

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References


