Performance Comparison of Modulation and Sorting Methods for Modular Multilevel Converter

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Abstract. The modulation strategy of modular multilevel converter (MMC) needs to be combined with the sub-module (SM) redistribution strategy to maintain the stability of the SM capacitor voltage while working properly. The submodule (SM) switching frequency and the voltage balancing performance have been compared between two pulse width modulation (PWM) methods, i.e. carrier phase shift PWM (CPS-PWM) and submodule unified PWM (SUPWM), combined with two kinds of sorting methods, i.e. modulation wave compensation method and improved module selection method. The theoretical and simulation results show that when the number of sub-modules and the carrier frequency meet the requirements of ship propulsion, it is difficult for modulation wave compensation method to maintain good performance in different output frequency conditions. Using improved module selection method will increase the switching frequency of the device, but it has a higher performance in voltage balancing.

Introduction

A MMC has been widely used in the field of high-voltage direct-current transmission (HVDC) [1][2], and its use in high-power frequency modulation and speed regulation has attracted more and more attention[3]-[5]. Its great potential in ship electric propulsion was mentioned in [6]. The PWM method refers to the output performance of MMC, and the power consumption and voltage balance of SMs. All these are extremely important to propulsion converters.

Modulation method such as carrier phase shifted (CPS) modulation, nearest level modulation (NLM) and carrier disposition (CD) modulation are compared in view of the 31-level MMC applied to HVDC in [7], in which each modulation method is compulsorily paired with one SM voltage balance method to be studied as a whole without considering a flexible composition among them. In [8], CPS-PWM and pulse phase-shifted modulation were compared, but the comparison was not thorough. The latter only serves the function of simplifying the program of the former, with little essential difference between the two.

Now, CPS-PWM [9] is mostly adopted for multilevel inverters. It is applicable to a multiphase motor drive system with the moderate number of levels. Because it is easy to implement and expand. Recently the SUPWM [10] has also been used in MMC. It is worth of further study. The promising sorting methods are modulation wave compensation method [11] and improved module selection method [12].

Which modulation method is better and more suitable for MMC ship propulsion, is lack of relevant research. This paper will focus on comparing the performance of voltage balancing, switching frequency and program complexity of CPS-PWM and SUPWM, in order to obtain more suitable strategy for ship propulsion.

The Basic Structure of MMC

The basic MMC topology includes the arms, consisting of some SMs connected in series. Fig.1 shows the topology of three-phase MMC drive.
As shown in Fig. 1, the typical SM structure of MMC is a half-bridge structure. This structure can output two kinds of level, 0 and $U_c$. Assuming the number of SMs of each arm is $N$, the $N+1$ level voltage can be output by controlling the on-off action of each SM.

Owing to the flexibility of MMC structure, a conventional multilevel modulation method can be applied to MMC through some improvement.

### Pulse Width Modulation Method

Compared with other PWM methods, CPS-PWM and SUPWM are suitable for the ship electric propulsion MMCs. This section gives an account of these two modulation methods.

There is little difference between the classical CPS-PWM and CPS-PWM for MMC. The modulation wave is compared with a set of triangular carrier waves with a certain phase shift, and a group of PWM signals are generated and allocated to each SM. The MMC with $N$ SMs per arm needs $N$ triangular carriers, with the phase difference between two adjacent carriers as $2\pi/N$. The total sum of PWM waveforms, which also represents the time-varying on-state number of SMs per arm, can be obtained by adding PWM signals of SMs in an arm together. The arm output waveform creates by use of CPS-PWM is shown as below.

### SUPWM

SUPWM is an improvement on NLM. The staircase wave is determined by the same procedure of NLM, and the error between staircase wave and modulation wave is compensated by a SM output modulated by duty cycle.

The staircase waves of the upper and lower arm are expressed as

$$
\begin{align*}
N_{pj} &= \text{floor}\left(\frac{n_{pj}}{U_{dc}}\right) \\
N_{nj} &= \text{floor}\left(\frac{n_{nj}}{U_{dc}}\right)
\end{align*}
$$

(1)

where floor(.) indicates floor function.

The duty cycle of the compensating SM in the upper and lower arm in x-phase can be calculated by (2).
\[
D_{p} = \frac{u_{m}}{U_{dc}} - \text{floor}\left(\frac{u_{m}}{U_{dc}}\right)
\]
\[
D_{n} = \frac{u_{m}}{U_{dc}} - \text{floor}\left(\frac{u_{m}}{U_{dc}}\right)
\]

The SUPWM output can be divided into two parts: staircase wave and PWM compensation. The staircase wave acts \(2N\) times per cycle, and the PWM compensation further increases the switching action, which is related to the sampling frequency of the PWM compensation. Therefore, the equivalent switching frequency of the SUPWM output is determined by the sampling frequency of the PWM compensation. Let the frequency be \(f_{c2}\).

\[\text{Figure 3. Principle of PWM generation by SUPWM.}\]

**Sorting Method**

With the SM capacitors suspended in the MMC, the capacitor voltage will inevitably fluctuate during the operation, resulting in the voltage deviation of each capacitor. The state-of-art voltage balancing strategy is to sort the SMs according to the magnitude of the SM capacitor voltage and the direction of the arm current after the PWM outputs switching signals, and then to redistribute the signals to each SM. This procedure of PWM redistribution is also called sorting method. The switching actions of each SM is eventually determined by the sorting method.

In a MMC, all the SMs are not quite the same in switching frequency, which will result in uneven power loss. Therefore, an additional procedure of switching action redistribution is needed to keep the SM switching frequencies in average distribution.

As mentioned above, the PWM method for MMC is usually combined with the sorting method. The sorting method can not only balance the capacitor voltage of each SM but also average their switching frequencies. Therefore, this method should be taken into account when the SM switching frequencies of CPS-PWM and SUPWM are compared.

CPS-PWM can make the switching frequencies of SMs consistent without additional adjustment due to its natural capability of balancing the frequency. The SM’s switching frequency in CPS-PWM can be equal without additional adjustment for its natural capacity of frequency balance. In SUPWM, the SM switching frequency responsible for PWM compensation is higher, so it is necessary to adopt the PWM redistribution strategy or the sorting method to balance the SM switching frequency. The method mentioned in [11] is usually used.

In addition, the sorting method in [12] is relatively suitable for MMC with fewer SMs. It is adopted only when there is a change in the total number of conducting SMs. It is easy to use and suitable for CPS-PWM and SUPWM.

**SM Switching Frequency**

A simulation program for the one-phase MMC with resistance-inductance load is designed to compare the average performances of switching frequency produced by the two modulation methods with the sorting method added in.

According to [13], the SM switching frequency can be estimated as

\[
f_{sw} = \frac{n_{\text{add}}}{2\Delta t}
\]
where \( n_{\text{add}} \) represents the number of switching actions of PWM signal during the time \( \Delta t \). Every two switching actions match one switching period.

The simulation calculation of the switching frequencies of all SMs in one arm has obtained the maximum and minimum value, which are listed in Table 1.

Table 1. Comparison of Device Switching Frequencies According to Different Schemes.

<table>
<thead>
<tr>
<th>Modulation and sorting method</th>
<th>Maximum SM switching frequency (Hz)</th>
<th>Minimum SM switching frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPS-PWM without sorting</td>
<td>501</td>
<td>499</td>
</tr>
<tr>
<td>CPS-PWM with sorting in [12]</td>
<td>500</td>
<td>438</td>
</tr>
<tr>
<td>SUPWM with sorting in [12]</td>
<td>551</td>
<td>670</td>
</tr>
</tbody>
</table>

All the schemes in Tab. 1 can guarantee the stable operation of the MMC at the rated frequency, but much difference exists among the switching frequency of SMs.

The Performance of Voltage Balancing

MMC for ship propulsion is needed to operate in different output frequency, thus the performances of voltage balancing should be analyzed in different frequency condition. Table 2 shows the simulation results of the voltage balancing performance of methods in 20Hz and 2Hz.

Table 2. Comparison of Voltage Balancing Performance in 20Hz and 2Hz.

<table>
<thead>
<tr>
<th>Modulation and sorting method</th>
<th>Voltage max deviation among SMs in 20Hz (p.u.)</th>
<th>Voltage max deviation among SMs in 2Hz (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPS-PWM without sorting</td>
<td>0.6434</td>
<td>0.7513</td>
</tr>
<tr>
<td>SUPWM with sorting in [11]</td>
<td>0.2215</td>
<td>0.6794</td>
</tr>
<tr>
<td>CPS-PWM with sorting in [12]</td>
<td>0.2466</td>
<td>0.2296</td>
</tr>
<tr>
<td>SUPWM with sorting in [12]</td>
<td>0.2410</td>
<td>0.2101</td>
</tr>
</tbody>
</table>

SUPWM with sorting in [11] shows a great performance in 20Hz, but it has large deviation in 2Hz. Its instability indicates it is not suitable for the MMC ship propulsion in a wide frequency range. And SUPWM with sorting in [12] shows best performance among these methods.

Summary

The theoretical and simulation results show that when the number of sub-modules and the carrier frequency meet the requirements of ship propulsion, it is difficult for modulation wave compensation method to maintain good performance in different output frequency conditions. Using improved module selection method will increase the switching frequency of the device, but it has the a higher performance of in voltage balancing is more significant. The SUPWM with improved module selection method is the most suitable strategy for MMC in ship propulsion.

References


