MODULATION STRATEGY AND VOLTAGE BALANCING CONTROL FOR MODULAR MULTILEVEL CONVERTERS

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ABSTRACT-The modular multilevel converter (MMC) has drawn attention due to its advantages of modular design, high efficiency and scalability, and excellent output waveforms with low harmonic distortion. For future high-power applications, the modular multilevel converter (MMC) has become one of the most promising converter topologies. One of the special characteristics of the MMC is the common-mode current which usually includes a dc component and even-order (mainly the second-order) harmonic component and also good overall control system is also vital for the MMC. A challenging issue of the MMC is the voltage balancing among arm capacitors. A new method for voltage balancing among arm capacitors, which is based on an improved space vector pulse-width modulation, is also presented. Space vector pulse width modulation is an Algorithm for the control of pulse width modulation. It's used for the creation of alternating current wave form, widely used to drive a 3 phase ac motor at varying speeds from DC. It avoids some major disadvantages found in present voltage balancing methods, such as dependence on computation-intensive voltage sorting algorithms, extra switching actions, interference with output voltage, etc. For both voltage-based and energy-based control methods, a control structure for MMC inverters is presented in this paper, which is suitable, and includes voltage balancing between the upper and lower arms. By using the simulation results verify the effectiveness of the proposed methods.

INTRODUCTION

A new method for voltage balancing among arm capacitors, which is based on an improved pulse-width modulation, is also presented in this paper. Recently, multilevel converters have attracted growing attentions and found themselves of high power and high/medium voltage applications such as high-voltage dc transmission (HVDC), flexible ac transmission systems (FACTS), industrial motor drives, utility-scale renewable energy systems, and so on. Among various multilevel converters, the diode-clamped or neutral-point clamped (NPC), flying capacitor (FC), and cascaded H-bridge (CHB) are the most studied topologies. Due to its modular structure the CHB topology then seems more suitable. However, for the applications requiring more than four or five levels, the NPC and FC topologies become less attractive due to significantly increased number of clamping diodes or FCs, higher power losses, and difficulty to balance the capacitor voltages. The space vector PWM (SVPWM) method is an advanced computation-intensive SVPWM method and is possibly the best method among the all PWM techniques for variable-frequency drive application. Because of its superior performance characteristics, it has been finding wide spread application in recent years. There are various variations of SVPWM that result in different quality and computational requirements. One major benefit is in the reduction of total harmonic distortion (THD) created by the rapid switching inherent to this SVPWM algorithm. A new centralized capacitor voltage balancing method along with an improved modulation method is proposed in this paper. This method as a whole has the following features:

1) In each arm of the MMC, compared with CPSPWM and conventional PDPWM only one voltage reference and one carrier are needed, which greatly reduces hardware requirement.

2) Among the power devices The SMs in one arm switch ON and OFF alternately, yielding an even distribution of switching frequency, and therefore, a good inherent voltage balancing capability.

3) In a closed-loop manner accurate voltage balancing is achieved.

4) In this paper unnecessary switching actions and high-frequency voltage sorting problem are both avoided. Modeling and control of the overall MMC system are also investigated.

Fig. 1. Topology of modular multilevel converter.

In this paper, to eliminate the need for separate dc sources, a modular multilevel converter (MMC or M2C) topology composed of half bridge or chopper sub modules (SM) was proposed. However, it requires a large number of isolated dc sources,
which are often provided by a bulky, multi winding transformer together with a series of rectifiers. It has become more and more attractive due to the modular structure, common dc-bus, distributed dc capacitors, easy grid connection, simple realization of redundancy, etc.

The present voltage balancing methods can be roughly categorized into two groups: distributed methods and centralized methods. The distributed methods keep the voltage of each capacitor close to its reference value through closed-loop control, and usually with carrier phase-shifted pulse-width modulation (CPSPWM). For the PWM process the balancing control is carried out with a modification of the modulating signal. It can achieve good voltage balancing when the switching frequency of each SM is high enough. However, changing the modulating signals of the SMs may affect the power quality at ac side. Centralized methods achieve voltage balancing at the PWM stage. Depending on capacitor voltages and arm current polarities they select certain SMs for certain switching states therefore these are also called module selection methods. These methods are usually (but not necessarily) used with phased position PWM (PDPPWM).

Space vector pulse width modulation is applied to output voltage and input current control. This method is an advantage because of increased flexibility in the choice of switching vector for both input current and output voltage control. It can yield useful advantage under unbalanced conditions. The three phase variables are expressed in space vectors. For a sufficiently small time interval, the reference voltage vector can be approximated by a set of stationary vectors generated by a matrix converter.

A new method which only looks up and adjusts the capacitors with the highest and lowest voltages, the high-frequency voltage sorting is still required. It brings low-frequency ripples into the capacitor voltages, and the ripple frequency is inversely proportional to the number of SMs in one arm. Consequently, larger capacitors are required to suppress the ripple voltage. Furthermore, the open-loop control cannot guarantee the voltage balancing under all operating conditions. Deng et al. proposed another centralized method with CPSPWM. It does not need to measure the arm currents, therefore the cost is reduced. However, high-frequency voltage sorting still remains. Moreover, when the number of SMs is large, this method is heavily dependent on high switching frequencies, which may not be possible.

**MODELING AND CONTROL STRUCTURE**

**A. Converter Topology**

Fig. 1 shows the topology of a typical three-phase MMC. Each phase leg of the MMC consists of two arms. Each arm has N identical SMs and one smoothing inductor. Each SM has two power semiconductor switches (S1 and S2) representing two IGBTs (or other types) with freewheeling diodes and one capacitor (C).

**B. Modeling and Control Structure**

The SMs in each arm can be regarded as controlled voltage sources, and they are connected in series to form a controlled voltage source with higher voltage vP x and vNx(x = u, w). iP x and iNx are currents of the upper and lower arms. Vde and Vdc are dc-link voltage and current. vxs ac-output voltage of phase x (with respect to the midpoint of the dc-link)

1) Voltage/Current Control at AC Side:

According to Kirchhoff’s voltage law

\[
\begin{align*}
\frac{1}{2} V_{dc} &= v_{px} + L \frac{dv_{px}}{dt} + R i_{px} + v_{x} \\
\frac{1}{2} V_{dc} &= v_{px} + L \frac{dv_{px}}{dt} + R i_{px} - v_{x} 
\end{align*}
\]

(1)

According to Kirchhoff’s current law (KCL), ac current ix can be expressed as

\[
i_{x} = i_{px} - i_{Nx}
\]

(2)

Define a control variable v1x as

\[
v_{1x} = \frac{1}{2} (v_{px} - v_{Nx})
\]

(3)

Substituting (2) and (3) into (1) yields

\[
\frac{1}{2} L \frac{dv_{px}}{dt} + \frac{1}{2} R i_{x} = -v_{x} - v_{1x}
\]

(4)

In a closed-loop for grid-connected applications, the ac current (ix) is usually controlled. With this structure, all the current control methods in conventional two-level inverters can be applied.

2) Voltage/Current Control at DC Side: Define a control variable v2x as

\[
v_{2x} = \frac{1}{2} (i_{px} + i_{Nx})
\]

(5)

and circulating current i2x flowing through both the upper and lower arms as

\[
i_{2x} = \frac{1}{2} (i_{px} + i_{Nx})
\]

(6)

Substituting (5) and (6) into (1) yields

\[
L \frac{dv_{px}}{dt} + R i_{2x} = \frac{1}{2} V_{dc} - v_{2x}
\]

(7)

According to KCL

\[
I_{d} = \sum i_{px} = \sum i_{Nx} = \frac{1}{2} \sum (i_{px} + i_{Nx}) = \sum i_{2x}
\]

(8)

3) Total Energy Control in Each Phase-Leg:

To maintain a constant average capacitor voltage during each fundamental period, the voltages or energies stored in the capacitors of each arm should be controlled properly. The internal energies of the arms shown below are chosen as dynamic control variables

\[
W_{Cpx} = \sum_{j=1}^{N} \left( \frac{1}{2} C_{V Cpx} \right) = \frac{1}{2} C \sum_{j=1}^{N} (v_{Cpx})^2
\]

(9)

\[
W_{Cnx} = \sum_{j=1}^{N} \left( \frac{1}{2} C_{V Cnx} \right) = \frac{1}{2} C \sum_{j=1}^{N} (v_{Cnx})^2
\]

(10)

The total energy (W(ΣCx)) and the differential energy (W(ΔCx)) in each phase-leg are

\[
W(\Sigma Cx) = W_{Cpx} + W_{Cnx}
\]

(11)
\[ W_{\text{CX}} = W_{\text{CPX}} - W_{\text{CNX}} \quad (12) \]

Ignoring power losses, the power relationships are
\[
\frac{dW_{\text{CPX}}}{dt} = \left( \frac{1}{2} V_{dc} - V_x - L \frac{di_x}{dt} - Ri_x \right) i_x \quad (13)
\]
\[
\frac{dW_{\text{CNX}}}{dt} = \left( \frac{1}{2} V_{dc} + V_x - L \frac{di_x}{dt} - Ri_x \right) i_x \quad (14)
\]

Since to filter the switching frequency harmonics the inductors in each phase-leg are used, the ac-side voltage and current can be assumed to be sinusoidal
\[
\begin{align*}
V_x &= V_x \sin(\omega t) \\
i_x &= I_x \sin(\omega t - \theta)
\end{align*}
\]

\[
\sum p_{12x} = -2L \frac{di_x}{dt} + i_{2x} \quad (16)
\]

4) **Differential Energy Control in Each Phase-Leg:**

Derivation of the differential energy can be represented as
\[
\text{where } \Delta \text{ represents the fundamental component of } dW_{\text{DC}} dt.
\]
\[
i_{2x} = I_{1x} \sin(\omega t + \varphi_x) \\
\approx p_{0\text{cx}} + p_{1\text{cx}} + p_{2\text{cx}} \quad (17)
\]
\[
p_{0\text{cx}} = -v_x I_{1x} \cos(\varphi_x) - R I_{1x} I_x \quad (18)
\]

5) **Overall Control Structure:** The total energy control, differential energy control, circulating current control, and ac current control are all included.

Based on the aforementioned analyses, for MMC operating as an inverter an energy-based overall control structure is presented. To simplify the computation all burden, the capacitor voltages within one arm are supposed to be balanced, i.e.
\[
\begin{align*}
W_{\text{CPX}} &= \frac{1}{2} C \sum_{n=1}^{N} (V_{\text{CPX}})^2 \\
W_{\text{CNX}} &= \frac{1}{2} C \sum_{n=1}^{N} (V_{\text{CNX}})^2
\end{align*}
\]

The arm reference voltages can be derived from (3) and (5) as
\[
\begin{align*}
V_{\text{PX}} &= V_{2x} + V_{1x} \\
V_{\text{RX}} &= V_{2x} - V_{1x}
\end{align*}
\]

**IMPROVED MODULATION METHOD**

This paper proposes an improved PDPWM, which requires much less hardware comparing units, but can provide excellent performance with inherent voltage balancing. PDPWM is one of the most important modulation methods for MMC, using one voltage reference and a group of level shifted triangular carrier waves. However, powerful microcontroller chips with multiple modulation modules are required especially when the number of SMs is high, e.g., tens to hundreds.

Space vector pulse width modulation (SVPWM) is an algorithm for the control of pulse width modulation (PWM). It is used for the creation of alternating current (AC) waveforms; most commonly to drive 3 phase AC powered motors at varying speeds from DC using multiple class-D amplifiers. There are variations of SVPWM that result in different quality and computational requirements. One active area of development is in the reduction of total harmonic distortion (THD) created by the rapid switching inherent to these algorithms.

![Fig. 2. Total energy control.](image)

\[
p \sum_{x=1}^{x} = -2L \frac{di_x}{dt} + i_{2x}
\]

**Fig. 3. Differential energy control.**

In Fig. 4 the red dotted-line box indicates the closed-loop current control in applications like grid-connected converters. In the energy-based control structure in Fig. 4, Large signal models are used which guarantees large signal stability.

![Fig. 4. Energy-based control structure of MMC operating as an inverter.](image)

However, if direct capacitor voltage control (i.e., voltage-based control) is needed, the structure can be easily modified as shown in Fig. 5. Voltage-based control is more intuitive, but small-signal linearized models have to be used and large signal stability is difficult to guarantee at the controller design stage.

![Fig. 5. Modification from energy-based control into voltage-based control.](image)
Suppose the average value of the capacitor voltages in each arm is $V_c$, then the voltage reference $v$ can be separated into an integral part and a fractional part, as shown in (27)

$$v = (n - 1)V_c + dV_c$$

(21)

Where $n = 1, 2, \ldots, N$, and $0 \leq d \leq 1$. That means, during each carrier period, only the $n$th SM operates in PWM mode (or switching mode), $(n - 1)$ SMs (from 1 to $n - 1$) at ON state, and $(N - n)$ SMs (from $n + 1$ to $N$) at OFF state.

$$v_{pwm} = (n - 1)V_c + v_p$$

(22)

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**Fig. 6.** Improved PDPWM with single reference and single carrier: (a) waveforms of reference and carrier; (b) implementation.

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**Fig. 7.** Pulse distribution for PDPWM with four SMs in one arm: (a) expected pulse waveform; (b) direct pulse distribution; (c) proposed alternate pulse distribution.

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**Fig. 8.** Flowchart of alternate pulse distribution (implemented in an FPGA).

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**Fig. 9.** Proposed capacitor voltage balancing for MMC: (a) negative arm current; (b) positive arm current.

The proposed modulation method yields even distribution of switching frequency among power devices, which is similar to CPSPWM. The complexity and hardware cost of this algorithm are low and do not increase with the number of SMs. Nonetheless, the hardware cost of the proposed method is much lower since it does not need separate PWM comparator for each SM.

**VOLTAGE BALANCING CONTROL**

A new voltage balancing control method based on the improved PDPWM is presented in this paper, which does not need voltage sorting algorithm and does not cause extra switching actions.
The inherent voltage balancing capability of the improved PDPWM method is fairly good. However, some non-ideal factors, e.g., differences in the SMs’ losses and circuit parameters, can still disrupt the balance of capacitor voltages. Fig. 11 shows the control block diagram, where \( \Delta \) is used for the computation of the time delay (\( \Delta t \)).

\[
\Delta t = \frac{\Delta \tau}{T_{cr}}
\]

(23)

\( T_{cr} \) is the carrier period. Thanks to the improved modulation method, a low bandwidth of the balancing control system can be selected. The upper limit of \( \Delta t \) in Fig. 10 can also be set to a low value, e.g., 10%.

Based on the assumption the comparison on cost is that the number of SMs within one arm is high. A comparison of present voltage balancing methods and the proposed method, which encompasses a broad range of features, is presented in Table I.

**TABLE I: COMPARISONS OF VOLTAGE BALANCING METHODS**

<table>
<thead>
<tr>
<th>Methods</th>
<th>Balanced accuracy</th>
<th>Dynamics</th>
<th>Switching frequency</th>
<th>Setting</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distributed control [12-15]</td>
<td>Medium</td>
<td>Medium</td>
<td>Unchanged</td>
<td>No</td>
<td>High</td>
</tr>
<tr>
<td>Modulation control</td>
<td>High</td>
<td>High</td>
<td>Increased</td>
<td>Yes</td>
<td>Low</td>
</tr>
<tr>
<td>Reduced switching frequency</td>
<td>Medium</td>
<td>Fast</td>
<td>Decreased</td>
<td>Yes</td>
<td>Low</td>
</tr>
<tr>
<td>Selective external loop control [12]</td>
<td>High</td>
<td>High</td>
<td>Decreased</td>
<td>Yes</td>
<td>Low</td>
</tr>
<tr>
<td>One loop control</td>
<td>Medium</td>
<td>Slow</td>
<td>Unchanged</td>
<td>No</td>
<td>High</td>
</tr>
<tr>
<td>Modulation [21]</td>
<td>Low</td>
<td>Low</td>
<td>Unchanged</td>
<td>No</td>
<td>Low</td>
</tr>
<tr>
<td>Proposed method</td>
<td>High</td>
<td>Medium</td>
<td>Unchanged</td>
<td>No</td>
<td>Low</td>
</tr>
</tbody>
</table>

If the arm current is negative, the SM with the highest voltage is switched OFF with a delay, while the SM with the lowest voltage is switched ON with the same delay. This scheme can be realized as follows.

**FIG. 12: CAPACITOR VOLTAGES DURING START-UP**

**A. PROPOSED VOLTAGE BALANCING CONTROL SCHEME**

In this paper, the balancing action is only applied to the SMs with the highest and lowest voltage, and the control algorithm is executed at a low frequency (\( f_{cr}/N \)). In the improved PDPWM, the imbalance among capacitor voltages develops slowly, therefore at the switching frequency (\( f_{cr} \)), the balancing control needs not to be executed and it needs not to adjust all the SMs. To satisfy the charge balance, if arm current is positive, the pulse width of the SM with highest voltage is reduced. The opposite thing happens when the arm current is negative while the pulse width of the SM with lowest voltage is increased by the same amount.

**TABLE II: PARAMETERS OF THE THREE-PHASE MMC FOR SIMULATION**

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated active power: ( P_c )</td>
<td>2 MW</td>
</tr>
<tr>
<td>Rated reactive power: ( Q_c )</td>
<td>0.5 MVar</td>
</tr>
<tr>
<td>Line voltage (rms): ( V_{dc} )</td>
<td>6 kV</td>
</tr>
<tr>
<td>Line (or ac) frequency: ( f_l )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>DC-link voltage: ( V_{dc} )</td>
<td>10 kV</td>
</tr>
<tr>
<td>Arm inductance: ( L )</td>
<td>2 mH (3.6%)</td>
</tr>
<tr>
<td>Arm equivalent resistance: ( R )</td>
<td>0.05 ( \Omega )</td>
</tr>
<tr>
<td>No. of SMs in each arm, ( N )</td>
<td>4</td>
</tr>
<tr>
<td>SM capacitor: ( C )</td>
<td>2 mF</td>
</tr>
<tr>
<td>Rated capacitor voltage: ( V_c )</td>
<td>2.5 kV</td>
</tr>
<tr>
<td>Switching frequency: ( f_{sw} )</td>
<td>2 kHz</td>
</tr>
<tr>
<td>Equivalent switching frequency in one arm: ( f_{sw} )</td>
<td>8 kHz</td>
</tr>
</tbody>
</table>

**FIG. 13: CAPACITOR VOLTAGES, UPPER/LOWER ARM CURRENTS, AND AC CURRENT IN STEADYSTATE.**
Fig. 14. Output voltages, output currents, arm currents, and capacitor voltage during sudden load changes.

**B. Selection of Time Delay \( \Delta t \)**

The difference (\( \Delta v_C \)) between the highest voltage (\( v_{C_{\text{max}}} \)) and lowest voltage (\( v_{C_{\text{min}}} \)) is nearly constant, which should be zero when the voltage balancing is achieved. When the imbalance within one arm occurs, the average values of the capacitor voltages are different, but their low frequency ripples vary with the same amplitude and in the same direction. Therefore, \( \Delta v_C \) is used as the error and a simple P or PI controller is adopted to adjust the unbalance.

**C. Discussion**

Compared with the method proposed so higher balancing accuracy can be achieved, since the control error in the proposed method is a dc component while the errors contain low-frequency ripples. To find out SMs with the highest and lowest voltages. The method avoids the usage of a full sorting algorithm since it only needs. Therefore, the computational burden is reduced, especially when the number of SMs is fairly high.

**SIMULATION RESULTS**

To verify the proposed control system, a three-phase MMC inverter with a resistor-inductor load is developed by MATLAB/Simulink software, and the parameters are summarized in Table II. PI controllers are used for total energy control, differential energy control, and circulating current control in the simulations.

**TABLE III: PARAMETERS OF THE THREE-PHASE MMC FOR EXPERIMENT**

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated active power: ( P_r )</td>
<td>3 kW</td>
</tr>
<tr>
<td>Line voltage (rms): ( V_{lin} )</td>
<td>228 V</td>
</tr>
<tr>
<td>Line (or ac) frequency: ( f_l )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>DC-link voltage: ( V_{dc} )</td>
<td>460 V</td>
</tr>
<tr>
<td>Arm inductance: ( L )</td>
<td>4.62 mH</td>
</tr>
<tr>
<td>Arm equivalent resistance: ( R )</td>
<td>0.1 ( \Omega )</td>
</tr>
<tr>
<td>No. of SMs in each arm: ( N )</td>
<td>( N )</td>
</tr>
<tr>
<td>SM capacitor: ( C )</td>
<td>560 ( \mu F )</td>
</tr>
<tr>
<td>Rated capacitor voltage: ( V_C )</td>
<td>200 V</td>
</tr>
<tr>
<td>Switching frequency: ( f_{sw} )</td>
<td>2 kHz</td>
</tr>
<tr>
<td>Equivalent switching frequency in one arm: ( f_{sw_{\text{arm}}} )</td>
<td>4 kHz</td>
</tr>
<tr>
<td>Load resistor (Y-connected): ( R_L )</td>
<td>24.5 ( \Omega )</td>
</tr>
</tbody>
</table>
Fig. 16. Line voltages and currents with step decrease of load.

Fig. 17. Capacitor voltages, arm currents, and ac current with and without differential energy control.

Fig. 18. Spectral analysis of line voltage (a) without load.

Fig. 19. Capacitor voltages, arm currents, and ac current with and without voltage balancing control.

CONCLUSION
A new method for voltage balancing among arm capacitors, which is based on an improved space vector pulse-width modulation, is presented. It avoids some major disadvantages found in present voltage balancing methods, such as dependence on computation-intensive voltage sorting algorithms, extra switching actions, interference with output voltage, etc. Space vector pulse width modulation is an Algorithm for the control of pulse width modulation. It's used for the creation of alternating current wave form, widely used to drive a 3 phase ac motor at varying speeds from DC. The improved PDPWM method distributes the gating pulses alternately among the SMs within one arm every N (number of SMs within one arm) several carrier periods. Single reference and single carrier (for one arm) used in the modulation reduce the control hardware requirement. For medium- and high-voltage applications, these features make the proposed balancing control method a more suitable solution, where the number of SMs in each arm can be fairly high. A general-purpose control structure is also proposed, which is adaptable for various control modes. Simulation results verified the good performances of the MMC system with the proposed methods. The performances of the improved modulation and balancing control are found to be satisfactory except for some extreme cases where the SM switching frequency drops below 100 Hz. For both voltage-based and energy-based control methods a control structure for MMC inverters is presented in this paper, which is suitable, and includes voltage balancing between the upper and lower arms. By using the simulation results verify the effectiveness of the proposed methods.

REFERENCES


