THD Minimization of Modular Multilevel Converter With Unequal DC Values

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Abstract—Different modulation techniques used to control multilevel converters can be classified based on the selected converter topology and optimization goals. Among all proposed modulation methods low switching frequency modulation techniques are very popular for multilevel converters yet non-real time low switching frequency methods cannot be applied to multilevel converters with unequal or varying DC values because these modulation techniques rely on look up tables and the size of look up tables will be huge in this case. This paper proposes a new modular multilevel converter (MMC) structure with unequal DC values. Some well-known low switching frequency modulation techniques and the commonly used PWM based methods are compared and using the new low switching frequency modulation technique called minimal total harmonic distortion (THD) modulation for MMC with unequal DC values is proposed. The PSCAD simulation results show that the new converter topology with unequal DC values has much lower THD compared to the typical MMC. Modulation algorithm is implemented in digital signal processor (DSP) and controller hardware in the loop (CHIL) implementation in RTDS verifies the real-time performance of the algorithm.

I. INTRODUCTION

Recent advancements in voltage source converter (VSC) topologies that increase their power rating by adopting higher dc operating voltage, lower semiconductor losses and elimination of ac side filters have made them more attractive in many applications. Modular multilevel converter (MMC) is an emerging multilevel converter topology introduced in 2001 and it is highly appealing for medium and high voltage applications [1]. MMC modulation approaches have been divided to three main categories: Pulse width modulation (PWM), staircase modulation and Space vector modulation (SVM) [1-3]. The most common modulation technique used for MMC so far is phase shifted or carrier shifted PWM (CS-PWM) method [4-7]. The main drawback of the typical PWM based methods is the increased switching losses of the converter switches, which is a big concern in systems with high number of sub modules. The SVM based techniques have also been used for MMC converters. SVM based modulation generally provides good utilization of the DC-link voltage, are simple to implement and can operate with reduced switching frequencies. However, as the number of voltage levels increases, the number of the redundant states increases, which in turn increases the complexity of the design in order to select the proper states for optimized operation. There are also some non-conventional modulation techniques such as SHE-PWM, which rely on look up tables. Staircase modulation renders low switching frequencies and a staircase waveform will be generated, following a sinusoidal envelope [7]. In this paper a new configuration is proposed for MMC, which uses unequal DC values, and minimal THD modulation technique, which is a staircase-based modulation, is used to switch the proposed MMC. THD and harmonics are compared with the typical MMC converter switched with CS-PWM. The proposed configuration is a good candidate for medium power applications such as PV inverters; drive applications or any other application that requires high voltage quality.

II. MMC SYSTEM STRUCTURE AND OPERATION PRINCIPLE

The single-phase configuration of Modular Multilevel Converter (MMC) topology is shown in Fig. 1. MMC consists a series of half-bridge sub-modules, which are cascaded in series to form the phase-legs of the converter. Each phase-leg is made of an upper and a lower arm and each arm includes some series connected sub-modules. The arm inductor is necessary to limit the short circuit and circulating currents through the phase-leg. Sub-modules are...
connected in series and arm current flows through each of the sub-modules and affects the voltage of the capacitor. The capacitors are charged when a positive current flows through the arm of the converter, they discharge if arm current is negative and their voltage remains constant in case the sub-modules is not connected to the arm of the converter. The phase-legs of the converter can be configured either for single-phase or three-phase applications [8]. From Fig. 1, the upper and lower arm equations can be derived for the phase-leg of the converter. Each arm of the converter can be considered as a controllable voltage source with a value that depends on number of sub-modules in that arm and their switching states. The two switches in each sub-module are complementary and table I shows the sub-module output voltage in different switching states [9-13].

Equations (1)-(6) describe the operation principle of MMC, \( S_{sm} \) is the switching state of each SM and \( V_C \) the voltage of the SM. The output current \( (i_{out}) \) is defined in (4) as the difference between the upper and lower arm current and (5) defines the circulating current within the arms of the converter \( (i_{circ}) \) as one-half of the sum of the upper and lower arm currents. The output and the arm currents of the converter depend on the switching states of the arm sub-modules and the modulation method of the converter. The modulation techniques and the derivation of the switching states of the SMs for the MMC are analyzed in the following section.

\[
V_{arm} = \sum_{i=1}^{N} S_{si} V_C + L_{arm} \frac{di_{arm}}{dt} + R_{arm} i_{arm} \tag{1}
\]

\[
\frac{V_{dc}}{2} - V_{upper} - R_{arm} i_{upper} - L_{arm} \frac{di_{upper}}{dt} - V_{middle} = 0 \tag{2}
\]

\[
\frac{V_{dc}}{2} + V_{lower} + R_{arm} i_{lower} + L_{arm} \frac{di_{lower}}{dt} - V_{middle} = 0 \tag{3}
\]

\[
i_{out} = i_{upper} - i_{lower} \tag{4}
\]

\[
i_{circ} = \frac{i_{upper} + i_{lower}}{2} \tag{5}
\]

\[
V_{out} = \frac{V_{upper} - V_{lower}}{2} \tag{6}
\]

III. MODULATION TECHNIQUE

The optimal modulation techniques are usually designed to meet specific harmonic limitations with minimum switching frequencies, additional filters or voltage levels. Elimination of low order harmonics is usually an important goal and few publications have focused on this issue in modular multilevel converters. A multilevel selective harmonic elimination (SHE) method has been recently proposed for MMC, which offers tight control of low-order harmonics and has the lowest switching frequency for power semiconductors among all modulation techniques [14]. SHE based methods have the crucial drawback of relying on look up tables with pre-calculated angles, which results in some problems in closed loop control of the system. A comparison of some famous low switching frequency modulation techniques is presented in table I.

No optimal modulation has been proposed for modular multilevel converter that gives the limitation of voltage THD. The minimal THD modulation presented here will deal with this concern. In the minimal THD modulation, the switching angles can be calculated in real-time and the implementation does not rely on the look-up tables. Another critical limitation of some optimal modulations is that they are not suitable for the multilevel inverters with unequal or variable voltage steps but minimal THD modulation does not deal with this limitation. The minimal THD modulation is designed for the staircase modulation and it has three important advantages: minimization of voltage THD, real-time calculation, and compatibility using the inverter with unequal or variable voltage steps. The modulation block will monitor DC voltages and the updated modulation magnitude and calculates a set of switching angles based the minimal THD criteria to achieve the minimum THD; the proof has
been presented in [15]. The calculations are rapid; therefore the switching angles can be figured out in real-time and no look-up tables are needed.

Assuming a basic staircase modulation as Fig. 4, there are s positive, s negative and a zero voltage stage and there will be a total of 2s+1 levels, which are defined as E₁, E₂,.., Es. The voltage levels may vary or they might be constant, also based on the value of DC voltages a switching pattern can be defined to build the desired shape. The quantities θ₁, θ₂,.., θₙ are the switching angles that indicate the on or off instant of switches of the sub-modules. These angles are calculated based on the voltage steps and modulation at each instant. The control system of MMC operates based on the defined control targets and sends the modulation and timing information to the minimal THD algorithm. The THD minimization algorithm receives voltage step and signals form the system controller and calculates the switching angle such that THD is minimum.

### TABLE II. COMPARISON OF SOME WELL-KNOWN LOW SWITCHING FREQUENCY MODULATION TECHNIQUES

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Optimization aim</th>
<th>Real time calculation</th>
<th>For varying steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Staircase modulation with elimination of low order harmonics</td>
<td>Elimination of lower order harmonics</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Selective harmonic elimination PWM with equal voltage steps</td>
<td>Elimination of low order harmonics</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Selective harmonic elimination PWM with unequal voltage steps</td>
<td>Elimination of low order harmonics</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Minimal THD modulation</td>
<td>Minimization of voltage THD</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The algorithm comprises the following two steps and the flowchart in Fig. 2 explains the calculations [15]:

Step 1. Calculation of the modulation

\[
\sum_{k=1}^{s} e_k \sqrt{1-(\mu_k \rho)^2} = m
\]

\[
e_k = \frac{E_k}{\sum_{l=1}^{s} E_l}
\]

\[
\mu_k = \frac{\sum_{l=1}^{s} E_l - E_k / 2}{\sum_{l=1}^{s} E_l - E_d / 2}
\]

Step 2. Finding the switching angles by evaluating

\[
\theta_k = \arcsin(\mu_k \rho) \quad k = 1, 2, ..., s
\]

At each instant the algorithm compares the calculated modulation with the modulation waveform from the converter control system and if the difference was less than a small pre-defined value (δ) it stops the iterations and calculates the switching angles from equation 10.

### IV. PERFORMANCE OF THE PROPOSED MODULATION TECHNIQUE

A modular multilevel converter with three sub-modules in each arm is simulated using PSCAD-EMTDC and modulated using the minimal THD modulation technique. The control structure of the MMC outputs the modulation waveform and phase (\(\omega t\) rad/s) of the system which are the inputs to the angle calculator control block and the switching angles are calculated in real time based on inputs at each instant then the sub modules of MMC are switched based on a staircase modulation to generate the target waveform using a set of switching angles. Fig.3 shows the overall layout of the proposed system. One of the main advantages of the minimal THD modulation technique is being applicable to multilevel converters with unequal DC voltages. This paper proposes an alternative structure is for MMC with unequal DC values for different sub-modules. The sub-modules can also have different switching frequencies to improve THD or in other words the sub-module or sub-modules with lower DC values can have higher switching frequencies to help the waveform shaping function or the output quality [16]. The proposed structure with unequal sub-module DC values also allows using
different semiconductors for different sub-modules to decrease the losses.

The proposed system is simulated for an MMC with three cells in each arm when the DC voltages have VDC, 2VDC, 3VDC ratios, when the DC sources are unequal more voltage levels can be generated which improves the converters output voltage quality if the additional levels are used effectively. The conventional modulation techniques do not allow using the additional levels because the sub-modules randomly turn on or off. Sometimes a capacitor voltage balancing technique is incorporated and capacitors are sorted based on their instantaneous voltages so the sub-modules with lowest or highest capacitor voltage are switched first based on the direction of the arm current. The minimal THD modulation allows using the additional generated voltage levels between the old voltage levels. At each switching angle, $\theta_1, \theta_2,..., \theta_6$ the sub-modules are selected to turn on or off based on the new target waveform which has more levels than the conventional one for the same topology with the similar number of sub modules.

Figs 5-7 show the output voltage waveforms of a voltage controlled MMC in volts; the output voltage generated using typical MMC structure and minimal THD modulation is shown in Fig. 5. The same topology is switched using carrier shifted modulation technique, which is a commonly used modulation technique for MMC and is shown in Fig.6. Fig. 7 shows the proposed solution, which has the lowest THD amongst all three waveforms.

Comparing Figs 5-7, MMC converter with three sub-modules in each arm which have unequal values of 1VDC, 2VDC, 3VDC ratio switched with minimal THD modulation has the lowest THD which is 7.3% compared to the 15.45% for the conventional MMC with carrier shifted PWM and 11.3% for the conventional MMC that uses minimal THD modulation. Figs 8 and 9 show the harmonic spectrum of the MMC output voltage using this two modulation techniques and it can be seen that Fig. 9 has more harmonics and smaller fundamental magnitude. The output of the proposed structure has the highest fundamental magnitude and smaller high order harmonics compared to the others. Fig. 11 shows a visual comparison of the THD value for three mentioned cases.

Table II. showed that one advantage of minimal THD modulation compared to other common fundamental frequency modulation techniques is online calculation of switching angles. Controller hardware in the loop is employed to verify the online performance of the algorithm. Firing signals are generated using a DSP controller and sent to RTDS using digital input ports. The power stage is modeled in RSCAD, which includes an MMC inverter with three half-bridge modules and an inductor in each arm. Table III shows specifications of the modeled system in RTDS. Fig.12 shows the digital input signals to RTDS, which is the pulse pattern, generated in the DSP controller and applied to the MMC switches in RTDS. The MMC output voltage generated in RTDS is shown in Fig.13.

<table>
<thead>
<tr>
<th>TABLE III. SYSTEM SPECIFICATIONS</th>
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<tbody>
<tr>
<td><strong>Rated active power</strong></td>
</tr>
<tr>
<td><strong>Rated line to line rms voltage</strong></td>
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<tr>
<td><strong>DC supply voltage</strong></td>
</tr>
<tr>
<td><strong>Number of SM in each arm</strong></td>
</tr>
<tr>
<td><strong>Rated frequency</strong></td>
</tr>
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</table>

Figure 3. Overall structure of the converter and modulation technique

Figure 4. Multilevel inverter phase voltage with staircase modulation

Figure 5. Output voltage, typical MMC structure, minimal THD modulation
Figure 6. Output voltage of typical MMC structure, PS-PWM

Figure 7. Output voltage of MMC with unequal dc sources using minimal THD modulation (proposed structure)

Figure 8. Typical MMC with equal DC values, Vo harmonic spectrum, minimal THD modulation

Figure 9. Typical MMC with equal DC values, Vo harmonic spectrum CS-PWM

Figure 10. MMC with unequal DC and minimal THD modulation, Vo harmonic spectrum

Figure 11. Comparison of the THD value in three different cases

Figure 12. Firing signal generation in RTDS

Figure 13. Output voltage waveform of MMC with unequal DC values modeled in RTDS using controller hardware in the loop
V. Conclusion

THD and loss are important concerns in power converters. This paper proposed an alternative structure for modular multilevel converter with unequal DC values for different sub-modules that uses minimal THD modulation technique for switching. The proposed structure showed an improvement in voltage quality comparing to the current solutions. Moreover, it allows using different type of semiconductors or different switching frequencies for different sub-modules, which can further improve the output quality and converter efficiency. The proposed system was modeled in PSCAD and voltage waveforms and their harmonic spectrums were shown and compared. Controller hardware in the loop was also implemented using RTDS to verify the online calculation of switching angles.

REFERENCES


