Capacitance and Inductance Selection of the Modular Multilevel Converter

Marcin Zygmanowski\textsuperscript{1}, Bogusław Grzesik\textsuperscript{1}, Radosław Nalepa\textsuperscript{2}
\textsuperscript{1}SILESIAN UNIVERSITY OF TECHNOLOGY
Faculty of Electrical Engineering, Dept. of Power Electronics, Electrical Drives and Robotics
ul. B. Krzywoustego 2
Gliwice, Poland
Tel.: +48 / (32) 237 12 47
Fax: +48 / (32) 237 13 04
E-Mail: marcin.zygmanowski@polsl.pl, URL: http://kener.elektr.polsl.pl

\textsuperscript{2}ABB CORPORATE RESEARCH CENTER
ul. Starowiślna 13a
Krakow, Poland

Acknowledgements
This work has been supported by ABB Corporate Research Center, Krakow, Poland.

Keywords
«High voltage power converters», «Multilevel converters», «Converter circuit», «Simulation»

Abstract
The paper presents a proposal for capacitance and inductance selection procedure of the modular multilevel converter. Two analysis criteria are taken into consideration, the circulating current and voltage ripple across submodule capacitors. Results are obtained numerically by using the converter averaged model based on state equations. In the modular multilevel converter operating under a direct modulation method, based on sinusoidal modulating signals, circulating currents flows through the converter arms. These currents are strongly dependant on the component parameters of the converter, such as: submodule DC-link capacitor capacitance and arm inductor inductance. Both components form a series resonance circuit in each converter arm. Resonance that occurs in the converter arm has to be avoided and therefore it is important to properly select component parameters while taking into account all possible resonances. Such components selection should be carried out at an early stage of the converter design.

Introduction
The modularity concept applied to power electronic converters is a very interesting idea, which allows increasing converter reliability and reducing the cost of maintenance, both factors being of great importance in high voltage and power applications. One of the most promising modular converters is the modular multilevel converter (MMC) presented in Fig. 1.a. This converter is particularly intended for HVDC systems [1], [2]. Nevertheless, it is also an interesting alternative for medium voltage applications, e.g. medium voltage electric drives [3], [4]. Such a wide range of application fields for a single topology makes it challenging to understand all important components selection and circuit operation aspects. The challenge does not disappear even if advanced numerical circuit simulations are deployed – simulation of the converter with specified parameters is not a substitute for sufficient understanding of this advanced circuit.

The most common MMC in literature is the converter based on half bridge converter submodules (SM in Fig. 1.a). The converter can be controlled by using different control strategies based on PWM [5]-[7] or low-switching frequency modulation [8] methods. One of the simplest modulation methods used in MMC is a direct modulation method which is based on sinusoidal signals [5], [9], [10].
In the MMC operating under direct modulation, an uncontrolled circulating current flows in each converter arm [11]. This current consists of a dc component, which corresponds to the power at the dc side of the converter, and an ac component, which increases power losses and voltage ripples across submodule capacitors. The ac component contains even-order harmonics [11]. There are various control algorithms which reduce the circulating current [9], [12], [13]. However, they generally increase complexity of the converter controller and demand large a number of values to be measured. This paper is focused on the selection of modular multilevel converter parameters based on circulating current resonances and capacitor voltage ripples. The selected parameters include: arm inductance and capacitance. Proper selection of such parameters can drastically reduce the circulating current ac component, converter power losses and submodule capacitor voltage ripples. However, the circulating current ac component has a resonant character, which makes the analysis complex. The parameter selection procedure is based on a number of iterative simulations using the averaged MMC model carried out in Matlab/Simulink. Apart from the selection procedure, this paper presents a review of the MMC literature focusing on selected MMC parameters.

Description of the converter model

Averaged MMC model

The three-phase modular multilevel converter with half-bridge converters contains $3 \times 2 \times 2n$ switches, which is a high number, particularly in the case of many submodules $n$. In cases when a fast performance time of converter simulation is required, an averaged MMC model is very useful. This model, which is based on the converter dynamic equations (1)-(8) [2], uses continuous arm voltages rather than switched voltages generated by using PWM or low switching frequency modulation techniques. The model allows representing both the dynamic behavior of the converter and its steady state operation. It is important to note that a converter operation is explained here using the one-phase averaged model given in Fig. 1.b but its results are also valid for the three-phase model.

In the one-phase model, phase denotations ($A$, $B$ or $C$) for all values are omitted for the sake of analysis simplicity. From the averaged MMC model the following set of equation can be written (1) in accordance with the Kirchhoff voltage law.
\[
\frac{V_{dc}}{2} = R_{armU}i_{armU} + L_{armU}\frac{d}{dt}i_{armU} + v_{armU} + e_v; \quad \frac{V_{dc}}{2} = R_{armL}i_{armL} + L_{armL}\frac{d}{dt}i_{armL} + v_{armL} - e_v
\] 

(1)

Arm voltages in upper arm \(v_{armU}\) and in lower arm \(v_{armL}\) are obtained by assuming that submodules are lossless

\[
v_{armU} = n_Uv_{CU}; \quad v_{armL} = n_Lv_{CL}.
\] 

(2)

According to the principal rule of direct modulation, the modulating signals in upper and lower arms are purely sinusoidal as

\[
n_U = \left(1 - m_a \sin(\omega t)\right)/2, \quad n_L = \left(1 + m_a \sin(\omega t)\right)/2,
\] 

(3)

where \(m_a\) is the modulation index. In Equation (2) \(v_{CU}\) and \(v_{CL}\) are sums of \(n\) submodule capacitor voltages in upper and lower arm respectively (Fig 1.a) given as

\[
v_{CU} = \sum_{k=1}^{n} v_{CUk}; \quad v_{CL} = \sum_{k=1}^{n} v_{CLK}.
\] 

(4)

Submodule capacitor voltages depend, in turn, on its capacitance \(C_{SM}\) and currents \(i_{CU}\) or \(i_{CL}\) as

\[
C_{SM}\frac{dv_{CUk}}{dt} = n_Ui_{armU}; \quad C_{SM}\frac{dv_{CLK}}{dt} = n_Li_{armL}.
\] 

(5)

It is assumed in (5) that each submodule in a given arm is controlled by the same modulating signal \(n_U\) or \(n_L\). Assuming that all capacitor voltages in the converter arm are balanced, e.g. by using the submodule selection method [1], sums of capacitor voltages (4) are equal to \(v_{CU} = n_v_{CUk}\) and \(v_{CL} = n_v_{CLK}\). Therefore, equation (5) can be rewritten to

\[
C_{arm}\frac{dv_{CU}}{dt} = n_Ui_{armU}; \quad C_{arm}\frac{dv_{CL}}{dt} = n_Li_{armL},
\] 

(6)

where \(C_{arm} = C_{SM}/n\) is referred to as the arm capacitance and corresponds to an equivalent capacitance of a series connection of capacitors of all submodules in the converter arm.

Due to the fact that both arms parameters are typically equal, \(R_{armU} = R_{armL} = R_{arm}\) and \(L_{armU} = L_{armL} = L_{arm}\), the upper and lower arm currents \(i_{armU}\), \(i_{armL}\) can be expanded to

\[
i_{armU} = i_V/2 + i_{cc}; \quad i_{armL} = -i_V/2 + i_{cc},
\] 

(7)

where \(i_V\) is the output current given as \(i_V = I_V\sin(\omega t - \phi)\) and \(i_{cc}\) is the circulating current, which flows through the DC-link circuit and other converter phases. The circulating current is a state variable.

From equations (1), (6) and (7) the state space representation of the one-phase MMC converter is

\[
\begin{bmatrix}
\frac{di_{cc}}{dt} \\
v_{CU} \\
v_{CL}
\end{bmatrix} =
\begin{bmatrix}
-R_{arm} & -n_U & -n_L \\
L_{arm} & 0 & 0 \\
L_{arm} & 0 & 0
\end{bmatrix}
\begin{bmatrix}
i_{cc} \\
v_{CU} \\
v_{CL}
\end{bmatrix} +
\begin{bmatrix}
\frac{V_{dc}}{2L_{arm}} \\
\frac{n_Ui_V}{2C_{arm}} \\
\frac{n_Li_V}{2C_{arm}}
\end{bmatrix}.
\] 

(8)

The state space representation (8) is a basis for the averaged MMC model carried out in Matlab/Simulink, which is used for simulation and validation of the parameter selection procedure.
Circulating current

The circulating current has been a subject of intensive studies in recent years [5], [9] and [11]. In a steady state of the MMC operating under direct modulation, the circulating current consists of a dc component together with even-order harmonics

\[ i_{cc} = I_{ccdc} + \sum_{h=1}^{\infty} I_{cch} \sin\left(h \omega t - \phi_h \right), \]  

(9)

where \( I_{ccdc} \) is the circulating current dc component, responsible for power delivery from or to the dc side of the converter, \( I_{cch} \) are harmonic amplitudes \( (I_{cch} \neq 0 \text{ for } h = 2n \text{ and } I_{cch} = 0 \text{ for } h = 2n-1, \text{ where } n = 1, 2, \ldots) \) and \( \phi_h \) is the phase shift angle of a given harmonic.

From [11] it can be seen that in the MMC, which operates under direct modulation with the assumption that the output current is purely sinusoidal (10), all odd-order harmonics have amplitudes equal to zero.

\[ i_V = I_V \sin(\omega t - \varphi) \]  

(10)

Among the existing even-order harmonics \( (h = 2n, \text{ where } n = 1, 2, \ldots) \) the second-order harmonic has the greatest contribution in the circulating current. The amplitudes of particular harmonics depend strongly on the resonance effect that can occur in both converter arms. This resonance is caused by harmonics in the sum of the arm voltages \( v_{armu} + v_{arml} \), which occur across both arm inductors with constant inductance \( 2L_{arm} \). For this specific resonance circuit, capacitance is not constant but time-varying, like modulating signals \( n_U C_{arm} \) and \( n_L C_{arm} \). In such a circuit, resonance occurs at the resonance angular frequency [11] given by

\[ \omega_r = \frac{1}{2} \frac{2 \left( h^2 - 1 \right) + m_a^2 h^2}{8 h^2 \left( h^2 - 1 \right)} \quad \text{for } h = 2n, n = 1, 2, \ldots \infty. \]  

(11)

In this paper, the arm inductance and capacitance are parameters for which the selection procedure is carried out. This selection procedure is limited to the converter steady state operation at the fixed fundamental frequency \( f_m = 50 \text{ Hz} \). Therefore, (11) is rewritten to

\[ L_{arm} C_{arm} = F(\omega, h, m_a) = \frac{1}{\omega^2} \frac{2 \left( h^2 - 1 \right) + m_a^2 h^2}{8 h^2 \left( h^2 - 1 \right)} \quad \text{for } h = 2n, n = 1, 2, \ldots \infty, \]  

(12)

where \( \omega \) is angular frequency \( (\omega = 2\pi \cdot 50 \text{ Hz} = 314.15 \text{ rad/s}) \) and \( L_{arm}, C_{arm} \) are the arm inductance and capacitance at which the resonance occurs. These parameters, as can be seen from (12), depend only on the fundamental angular frequency \( \omega \), its harmonic order \( h \), and the modulation index \( m_a \).

Typically, all the aforementioned parameters are constant during the converter operation excluding the converter operating as an inverter in drive applications where the modulation index and fundamental frequency are changed. Other operational parameters, like the output current phase-shift angle \( \varphi \), the output current amplitude \( I_V \) and the converter dc voltage \( V_{dc} \), have no effect on the resonance frequency but they can affect the circulating current harmonic amplitudes \( I_{cch} \) and their phase angles \( \phi_h \). This feature allows performing an analysis of a wide range of converter solutions with different rated powers, dc voltages or submodule numbers. In the analysis presented in this paper, the influence of the arm resistance \( R_{arm} \) on resonance frequencies or on the circulating current is not investigated. This is due to the fact that this resistance should be kept as low as possible in order to reduce the converter power losses regardless of the application. Equations (11) and (12) are valid only for low arm resistance \( R_{arm} \), which in this paper is set to \( R_{arm} = 100 \text{ m\Omega} \).

It should be noted that resonances in the circulating current constitute one criterion of the parameter selection procedure presented in this paper. The second criterion is based on the selection of arm capacitance, determined by the energy stored in the whole converter, which has been explained in the next paragraph.
Parameter selection procedure

Arm capacitance selection

In the voltage source converters the energy is stored in DC-link capacitors. The maximum energy stored in capacitors $E_{\text{Cmax}}$ is determined by the rated converter power $S_n$ and the energy-power ratio

$$EP = \frac{E_{\text{Cmax}}}{S_n}.$$  \hspace{1cm} (13)

This ratio varies depending on the converter application and typically is $EP = 10 \text{ J/kVA}$ to $50 \text{ J/kVA}$. Lower values mean a reduction of the converter cost but higher voltage ripples in the DC-link circuit. In this paper it is assumed that the same energy-power ratio is applicable to the modular multilevel converter.

At the beginning of the AC-DC converter design stage two main converter parameters are set. It is the rated converter power $S_n$ and rms value of the line-to-line voltage $V_{\text{ac, rms}}$ at the ac side of the converter or the voltage $V_{\text{dc}}$ at the dc side of the converter. Assuming that in the MMC there are no redundant submodules, the relation between ac side and dc side voltages is given as

$$V_{\text{ac, rms}} = \frac{m_a V_{\text{dc}}}{\frac{2}{\sqrt{3}}},$$  \hspace{1cm} (14)

where the modulation index $m_a$ can be changed from 0 up to $2/\sqrt{3}$. The maximum energy stored in DC-link capacitors of the three-phase MMC consisting of $6n$ submodules is given by

$$E_{\text{Cmax}} = 6n \frac{C_{\text{SM}}}{2} \left( \frac{V_{\text{dc}}}{n} \right)^2 = 3C_{\text{arm}} V_{\text{dc}}^2.$$  \hspace{1cm} (15)

Hence the arm capacitance $C_{\text{arm}}$ can be calculated using the energy-power ratio $EP$

$$C_{\text{arm}} = \frac{E_{\text{Cmax}}}{3V_{\text{dc}}^2} = EP \frac{S_n}{3V_{\text{dc}}^2}.$$  \hspace{1cm} (16)

As will be presented later, the arm capacitance, given as (16), is typically lower than 2 mF, due to the fact that the ratio $S_n/V_{\text{dc}}^2$, which has the dimension of the current, limits the rated current of the converter, load and other power supply components.

Table I presents major MMC parameters described in selected papers from the reference list. The arm capacitance in Table I is given as $C_{\text{arm}} = C_{\text{SM}}/n$, the maximum energy stored in capacitors $E_{\text{Cmax}}$ is calculated from (15) and the energy-power ratio $EP$ from (13).

Arm inductance selection

The role of the arm inductors $L_{\text{arm}}$ in the MMC is to suppress any high frequency components of the arm currents caused by differences in upper and lower arm voltages. These differences can exist for example, due to different switching times of converter switches.

From Table I it can be seen that different arm inductances $L_{\text{arm}}$ have been chosen in different references. The exact value of the arm inductance depends on the submodule capacitor voltage $V_{\text{dc}}/n$, the modulation technique, the switching frequency and an additional controller optionally used for suppressing the circulating current.

In this paper only direct modulation is considered as a modulation technique and the circulating current is not suppressed by any other control methods. It means that the circulating current has to be suppressed only by proper selection of the arm inductance $L_{\text{arm}}$. This can be done by avoiding resonances (12) that occur in the circulating current for the previously given arm capacitance $C_{\text{arm}}$, thus
\[ L_{\text{arm}} |_{C_{\text{arm}}=C_{\text{arm}}} = \frac{1}{C_{\text{arm}} \omega^2} \left( \frac{2 (h^2 - 1) + m_a^2 h^2}{8 h^2 (h^2 - 1)} \right). \]  

(17)

**Table I: MMC parameters from the reference list**

<table>
<thead>
<tr>
<th>Ref.</th>
<th>( V_{dc} ) (kV)</th>
<th>( S_n ) (kVA)</th>
<th>( C_{SM} ) (μF)</th>
<th>( L_{\text{arm}} ) (mH)</th>
<th>( n )</th>
<th>( C_{\text{arm}} ) (μF)</th>
<th>( E_{\text{Cmax}} ) (kJ)</th>
<th>( \text{EP} ) (J/kVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>45.0</td>
<td>36000</td>
<td>2000</td>
<td>N/A</td>
<td>21</td>
<td>95</td>
<td>578.6</td>
<td>16.07</td>
</tr>
<tr>
<td>[2]</td>
<td>25.0</td>
<td>30000</td>
<td>5000</td>
<td>3.00</td>
<td>10</td>
<td>500</td>
<td>937.5</td>
<td>31.25</td>
</tr>
<tr>
<td>[3]</td>
<td>0.5</td>
<td>10</td>
<td>3300</td>
<td>3.10</td>
<td>5</td>
<td>660</td>
<td>0.5</td>
<td>49.50</td>
</tr>
<tr>
<td>[4]</td>
<td>0.2</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>4400</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>[5]</td>
<td>8.8</td>
<td>6 228</td>
<td>3000</td>
<td>0.05</td>
<td>10</td>
<td>300</td>
<td>70.1</td>
<td>11.25</td>
</tr>
<tr>
<td>[7]</td>
<td>200.0</td>
<td>200000</td>
<td>4000</td>
<td>4.00</td>
<td>100</td>
<td>40</td>
<td>4800.0</td>
<td>24.00</td>
</tr>
<tr>
<td>[8]</td>
<td>60.0</td>
<td>75000</td>
<td>3330</td>
<td>0.80</td>
<td>12</td>
<td>275</td>
<td>2997.0</td>
<td>39.96</td>
</tr>
<tr>
<td>[9]</td>
<td>0.5</td>
<td>10</td>
<td>3000</td>
<td>4.67</td>
<td>5</td>
<td>660</td>
<td>0.5</td>
<td>49.50</td>
</tr>
<tr>
<td>[10]</td>
<td>3.38</td>
<td>2390</td>
<td>3000</td>
<td>0.02</td>
<td>4</td>
<td>500</td>
<td>25.8</td>
<td>10.77</td>
</tr>
<tr>
<td>[11]</td>
<td>4.85</td>
<td>3430</td>
<td>3000</td>
<td>0.03</td>
<td>6</td>
<td>375</td>
<td>35.3</td>
<td>10.31</td>
</tr>
<tr>
<td>[12]</td>
<td>6.12</td>
<td>4320</td>
<td>3000</td>
<td>0.04</td>
<td>8</td>
<td>300</td>
<td>42.1</td>
<td>9.74</td>
</tr>
<tr>
<td>[13]</td>
<td>10.59</td>
<td>7480</td>
<td>3000</td>
<td>0.06</td>
<td>12</td>
<td>250</td>
<td>84.1</td>
<td>11.24</td>
</tr>
<tr>
<td>[14]</td>
<td>6.0</td>
<td>N/A</td>
<td>2200</td>
<td>2.30</td>
<td>2</td>
<td>1100</td>
<td>1.03</td>
<td>–</td>
</tr>
<tr>
<td>[15]</td>
<td>0.1</td>
<td>N/A</td>
<td>1200</td>
<td>5.00</td>
<td>2</td>
<td>600</td>
<td>0.02</td>
<td>–</td>
</tr>
<tr>
<td>[16]</td>
<td>20.0</td>
<td>21061</td>
<td>26000</td>
<td>1.59</td>
<td>20</td>
<td>1300</td>
<td>1560.0</td>
<td>74.07</td>
</tr>
<tr>
<td>[17]</td>
<td>5.0</td>
<td>1500</td>
<td>4000</td>
<td>1.33</td>
<td>4</td>
<td>1000</td>
<td>75.0</td>
<td>50.00</td>
</tr>
<tr>
<td>[18]</td>
<td>50.0</td>
<td>15000</td>
<td>3500</td>
<td>3.6</td>
<td>10</td>
<td>350</td>
<td>2625.0</td>
<td>175.00</td>
</tr>
<tr>
<td>[19]</td>
<td>60.0</td>
<td>50000</td>
<td>3300</td>
<td>3.0</td>
<td>4</td>
<td>825</td>
<td>8910.0</td>
<td>178.20</td>
</tr>
<tr>
<td>[20]</td>
<td>400.0</td>
<td>56000</td>
<td>1000</td>
<td>1.0</td>
<td>200</td>
<td>5</td>
<td>2400.0</td>
<td>42.86</td>
</tr>
<tr>
<td>[21]</td>
<td>25.0</td>
<td>30000</td>
<td>5000</td>
<td>3.0</td>
<td>10</td>
<td>500</td>
<td>937.5</td>
<td>31.25</td>
</tr>
<tr>
<td>[22]</td>
<td>9.0</td>
<td>N/A</td>
<td>1900</td>
<td>1.0</td>
<td>9</td>
<td>211</td>
<td>51.3</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. 2: Location of resonance characteristics in the \( L_{\text{arm}}-C_{\text{arm}} \) plane: a) characteristics presenting resonance arm inductance \( L_{\text{arm}} \) according to (17) for different MMC operation conditions, b) arm capacitance \( C_{\text{arm}} \) and inductance \( L_{\text{arm}} \) of the MMC presented in papers from the reference list.

The resonance arm inductances \( L_{\text{arm}} \) given in (17) have been presented in Fig. 2.a for different modulation indices \( m_a = 0.1 \) or \( m_a = 1 \), purely sinusoidal modulating signals \( n_U, n_L \), harmonic orders \( h = 2 \) and \( h = 4 \) and for fundamental frequencies \( f_m = \omega/(2\pi) = 50 \text{ Hz} \) and reduced frequency \( f_m = 25 \text{ Hz} \).
As can be seen from Fig. 2.a, an increase of the modulation index \( m_a \) increases the product \( L_{arm}C_{arm} \). A similar situation takes place in the case of decreasing the fundamental frequency \( f_m \). For higher orders of the circulating current harmonics the product \( L_{arm}C_{arm} \) is drastically reduced. The region with potentially high current harmonic content limited by the resonance characteristics for \( m_a = 1, h = 2 \) and \( m_a = 0.1, h = 4 \) is indicated in Fig. 2.b. As is presented in Fig. 2.b, most of the authors of selected references have chosen the arm inductances which are higher than the value given in (17) \( (L_{arm} > L_{arm}) \). However, in some of the references the arm inductance is lower than \( L_{arm} \). The general rule is that the selected parameters should be outside the region of a potentially harmful circulating current. In reference [8], which has the parameters inside this region, the authors have proposed a novel control strategy guaranteeing the circulating current suppression. In this case the restrictions concerning the circulating current can no longer be applied.

The proper selection procedure should be restricted to particular values of harmonic order and modulation indices which are possible for the converter application. In a situation when the modulation index \( m_a \) is limited during the converter operation to values much closer to the maximum value \( m_a = 1 \), the region presented in Fig. 2.b can be narrower.

The exact answer to the question where the accepted value of the arm inductance \( L_{arm} \) lies on the \( L_{arm}-C_{arm} \) plane is more problematic. This is because at some points located even further from resonance arm inductances \( L_{arm} \), the circulating current can be still considerably high. The exact answer concerning the rms value of the circulating current can be obtained by performing a simulation of the MMC averaged model. The results of such simulations are presented in the next paragraph.

**Simulation results**

The parameters of the MMC simulation model are given in Table II. This model is simulated in \( 100 \times 100 = 10000 \) iterations, where arm capacitance \( C_{arm} \) changes from 20 \( \mu \)F to 2 mF, and the arm inductance \( L_{arm} \) from 50 \( \mu \)H up to 5 mH. The main result of each simulation is the rms value of the circulating current ac component given as

\[
I_{ccac,rms} = \sqrt{\frac{1}{T} \int_0^T (i_{cc} - I_{ccdc})^2 \, dt}
\]  

(18)

where \( i_{cc} \) is the circulating current, from (7) it is equal to \( i_{cc} = (i_{armL} + i_{armUL})/2 \), \( I_{ccdc} \) is a dc component of the circulating current, and \( T = 1/f_m \) is a period of the fundamental component. All the presented results were obtained for the steady state operation. The circulating current ac component (9) is a parameter that should be kept as low as possible in the MMC with properly selected arm capacitance and inductance.

In Fig. 3 the simulation results of the MMC operated with parameters given in Table II are presented. The rms value of the circulating current ac component \( I_{ccac,rms} \) is presented as a function of two variables: arm inductance \( L_{arm} \) and arm capacitance \( C_{arm} \) (Fig. 3.a). In this figure, two vertical lines for constant values of the arm capacitances \( (C_{arm} = 0.5 \text{ mF} \) and \( C_{arm} = 1 \text{ mF} \) are indicated. These lines, presenting the intersections of the \( I_{ccac,rms} \) function, have been shown in Fig. 3.b and Fig. 3.c as one variable function of the arm inductance.

**Table II: Parameters of the simulated MMC**

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage at the converter dc side</td>
<td>( V_{dc} )</td>
<td>5.0 kV</td>
</tr>
<tr>
<td>Output current amplitude</td>
<td>( I_V )</td>
<td>100 A</td>
</tr>
<tr>
<td>Fundamental frequency</td>
<td>( f_m )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Modulation index</td>
<td>( m_a )</td>
<td>1.0</td>
</tr>
<tr>
<td>Output phase shift angle</td>
<td>( \phi )</td>
<td>0 deg</td>
</tr>
<tr>
<td>Arm capacitance</td>
<td>( C_{arm} )</td>
<td>0.02, ..., 2 mF</td>
</tr>
<tr>
<td>Arm inductance</td>
<td>( L_{arm} )</td>
<td>0.05, ..., 5 mH</td>
</tr>
<tr>
<td>Arm resistance</td>
<td>( R_{arm} )</td>
<td>0.1 ( \Omega )</td>
</tr>
</tbody>
</table>
arm capacitance, $C_{\text{arm}}$ (mF)

0.5 1.2

arm inductance, $L_{\text{arm}}$ (mH)

1.3 5

Fig. 3:

Simulation results presenting the rms value of the circulating current ac component in the MMC with parameters given in Table II: a) as a function of $L_{\text{arm}}$ and $C_{\text{arm}}$, and b), c) as a function of the arm inductance $L_{\text{arm}}$ for given arm capacitances $C_{\text{arm}} = 0.5$ mF and 1 mF respectively.

In both functions the occurrence of resonance in the circulating current is evident. However, in Fig. 4, in order to prove the resonance character of the circulating current, its harmonic spectra have been presented for four points A-D from Fig. 3. Points A and C lie on the second-order harmonic resonance curve and therefore this harmonic has the largest amplitude in their spectra (Fig 4.a and Fig. 4.c). Harmonic spectra for points B and D are presented in Fig. 4.b and Fig. 4.d. For all points A-D the waveforms of the circulating current ac components ($i_{\text{ccac}} = i_{\text{cc}} - i_{\text{ccdc}}$) are shown in Fig. 4.e-4.h. The rms values $I_{\text{ccac, rms}}$ (in Fig. 3.b and 3.c) are compared to the output current rms value, $I_{\text{Vrms}} = 70.7$ A. The converter parameters are selected incorrectly when the rms value of the circulating current ac component $I_{\text{ccac, rms}}$ is higher than $I_{\text{Vrms}}$. Typically such parameters ($L_{\text{arm}}, C_{\text{arm}}$) lie between second-order harmonic and fourth-order harmonic resonance curves. However, for some arm inductances which place the operating point between both resonance curves, the circulating current can be at the acceptable level.

As can be seen in Fig. 3.a, when arm parameters $L_{\text{arm}}, C_{\text{arm}}$ are close to resonance parameters $L_{\text{armr}}, C_{\text{armr}}$ for smaller capacitances, the rms circulating current is higher than currents achieved for higher capacitances. The issue is illustrated in Fig. 5, where arm parameters are expressed by (12), $L_{\text{arm}} = L_{\text{armr}}$ and $C_{\text{arm}} = C_{\text{armr}}$ for $f_m = 50$ Hz, $h = 2$ (Fig. 5.a) and for $f_m = 50$ Hz, $h = 4$ (Fig. 5.b).

Fig. 4:

Circulating current ac component: a)-d) harmonic spectra at points A-D, e)-h) circulating current ac component waveforms for operation at points A-D.
As presented in Fig. 5.a or Fig. 5.b, resonances at lower arm capacitances give higher rms values of the circulating current. Moreover, for a low value of the arm capacitance, the arm inductance $L_{arm}$, being higher than $L_{armr}$, is significantly and impractically high. Therefore, in the opinion of the authors, arm capacitances lower than 0.5 mF ($C_{arm} < 0.5$ mF) should be avoided. Resonance at the fourth-order harmonic does not affect the rms value of the circulating current (Fig. 5.b) as strongly as the second-order harmonic. Therefore, the parameters in close proximity of the fourth-order harmonic resonance can be accepted.

During the simulation the averaged MMC model was used for calculating the arm capacitor voltage ripple. This voltage is defined as the peak-to-peak value of the sum of capacitor voltages defined in (4). The capacitor voltage ripple criterion is important from the point of view of a power electronic device safe operation. When higher voltage ripples exist in the DC-link circuit, all power electronic switches should be selected to withstand such conditions.

In Fig. 6 the simulation results of the capacitor voltage ripples are presented. The conclusions drawn on the basis of this analysis are similar to those obtained from the analysis of the circulating current. The authors suggest that the only converter parameters to be selected should be the ones which assure the capacitor voltage ripples lower than e.g. 10% $V_{dc}$, which are 1000 V in the presented example.

**Conclusions**

In this paper the MMC parameter selection procedure has been proposed. The method involves two steps. The first step is devoted to arm capacitance selection, which depends on the rated converter power and its voltage. Although many researchers proposed many different MMC parameters, the majority of them have similar arm capacitances, being not higher than 1.5 mF. This means that the theoretical results obtained in this paper are close to the results presented by other authors.
The second selection step is related to arm inductance which results in the avoidance of the second-order harmonic resonance. Moreover, it is important that the arm capacitance cannot be too low, for instance $C_{\text{arm}} < 0.5 \text{ mF}$, because it strongly influences the capacitor voltage ripple, which, in turn, influences the circulating current.

It should be emphasized that the presented MMC parameter selection procedure is applicable to modular multilevel converters controlled with direct modulation technique, for different power and voltage levels. All the achieved results are scalable.

Further research in this field can be focused on the MMC with different control strategies.

References


