A Novel Method on MMC Simulation Modeling with Detailed Capacitance Characteristics

Wujie Chao, Zhijun Tang, Guodong Lin and Zhicheng Li
State Grid Fujian Electric Power Research Institute, Fuzhou, Fujian 350007, China
tang_zhi_jun@126.com, 1141393587@qq.com, 244854212@qq.com, 1102298079@qq.com

Abstract: Modular multilevel converter shows the greatest advantage in HVDC transmission. However, high-level modular multilevel converter simulation is still difficult to achieve on the field of electromagnetic transient simulation due to complicated matrix calculations. In order to improve the accuracy of electromagnetic transient simulation for modular multilevel converters, a novel model based on controlled source equivalents is proposed by modifying the sub-module and arm models. The higher-order admittance matrix in the system is divided to perform further energy numerical equivalence to independent sub-modules, reducing a large number of nonlinear components in the circuit. Finally, the effect of the proposed simulation model was verified by electromagnetic transient simulation. The simulation results show that

1. Introduction
The modular multilevel converter (MMC) [1] shows great advantages in the application of high-voltage direct current (HVDC) transmission engineering and has become the development direction of this field in the future. In order to obtain better waveform quality and higher voltage levels, the number of sub-modules in each phase arm can reach hundreds in actual engineering applications [2]. Nowadays, there are many successful examples of modular multilevel converter HVDC transmission (MMC-HVDC) projects, such as Nan’ao three-terminal HVDC project [3], Zhoushan five-terminal HVDC project [4] and Xiamen HVDC project[5]. However, the operational data of the flexible HVDC transmission project is still insufficient. It is necessary to study the electromagnetic transient simulation modeling of the system. A large number of sub-modules on the arm will increase the computational complexity of the electromagnetic transient simulation modeling of the converter. Since every time the power electronic device operates in the EMTDC, its resistance value will change, and the admittance matrix needs to be re-triangulated or re-inverted. In the high-level MMC simulation, the simulation speed will be greatly reduced, taking up a lot of computer resources.

Some research work has been carried out on this issue. In [6], an MMC universal electromagnetic transient modeling method based on the controlled source equivalent is proposed, and the electrical decoupling of the MMC converter is achieved through the information transmission between the controlled voltage source and the controlled current source, since the sub-modules are not changed. Because of the structure, the simulation accuracy is high and the implementation method is simple. However, the simulation model still contains a large number of nonlinear devices, which is not suitable for the simulation of large-scale MMC applications. In [7], the MMC electromagnetic transient Thevenin equivalent model is proposed, the switching devices in the sub-modules are simplified as variable resistors, and then the two-port Thevenin circuit equivalents are implemented.
for the MMC. In the equivalent process, trapezoidal integral method is used for integral calculation. The model can reflect the sub-module's Thevenin's information in detail. The simulation accuracy is very high, but the equivalent process is more complex and it obviously increases when the high-level environment uses the equivalent method for simulation. In [8], by simplifying the structure of the MMC sub-module to reduce the complexity of the network to be solved, the simulation speed can be increased. However, since the sub-modules are still connected in series, the simulation time is significantly longer as the number of MMC levels increases. In [9], an average model is proposed to replace the MMC inverter arm with a controlled voltage source or a controlled current source, which greatly increases the simulation speed and changes the simulation speed without increasing the number of modules. However, the average model ignores the independence of the sub-module capacitance, simplify the internal operating characteristics of the MMC, and it is difficult to meet the research requirements of the converter control strategy.

According to the above analysis, the existing MMC simulation modeling method still has the problem of slow simulation speed. In order to solve the contradiction of the existing methods, a novel model is proposed in this paper.

2. MMC basic structure
The basic topology of MMC is shown in Figure1. The $U_{DC}$ is the DC bus voltage. Each arm consists of N sub-modules (SM) and a reactor $L$. In the actual project, the SM generally adopts a half-bridge SM (HBSM), as shown in Figure2. The sub-module realizes the input and removal of the sub-modules in the main circuit by controlling the IGBT switches $T_1$ and $T_2$. The single-directional channels provided by $D_1$ and $D_2$ are the storage capacitors. The fast bypass switch $S_1$ are used to implement sub-module protection under specific conditions to avoid device damage.

![Figure1. MMC topology diagram](image1)

![Figure2. Half-bridge MMC sub-module](image2)

3. Energy Equivalent Model
This method discusses the arm and the sub-module separately, making the two separate on the electrical structure. The cascade of a large number of switch tubes is avoided, and the node admittance matrix of the simulation modeling process is reduced in dimension.

1) The MMC is equivalent as shown in Figure 3. The arm is equivalent to the controlled voltage source in Figure 3 and the reactance $L$ is retained. The equivalent arm controlled source voltage $U_{RMn}$
\((n=a,b,c)\) is the sum value of the output voltage \(U_{smk}\) (\(1 \leq k \leq N\)) of the equivalent model of sub-module, as shown in Figure 3, the direction of the arm current \(I_{RMn}\) is positive.

2) The sub-module is equivalent to the equivalent sub-module in Figure 3. Sub-module switch tubes are simplified, regardless of on-resistance. Available sub-module work state quantity \(S_k\) is as shown in formula (1).

\[
\begin{cases}
S_k = 1, \text{ ON} \\
S_k = 0, \text{ OFF}
\end{cases}
\]  

(1)

The energy input change \(\Delta E_{sm}\) can be obtained from the sub-module of formula (2). \(\Delta E_{sm}\) will be converted into sub-module energy storage changes. Combined with the capacitor energy storage formula (3), the voltage update formula (4) can be obtained.

\[
\Delta E_{sm}(t) = U_c(t - \Delta t)I_c(t - \Delta t)
\]  

(2)

\[
\Delta E_{sm}(t) = \frac{1}{2}C(U_c^2(t) - U_c^2(t - \Delta t))
\]  

(3)

\[
U_c(t) = \sqrt{\frac{2\Delta E_{sm}(t)}{C} + U_c^2(t - \Delta t)}
\]  

(4)

The energy input change \(\Delta E_{sm}\) can be obtained from the sub-module of formula (2). \(\Delta E_{sm}\) will be converted into sub-module energy storage changes. Combined with the capacitor energy storage formula (3), the voltage update formula (4) can be obtained.

Finally, the output voltage of each sub-module on each bridge arm is added to obtain the voltage value of the equivalent voltage controlled source of the arm at the current moment.

4. Simulation verifying based on PSCAD/EMTDC
A five-level MMC model is built in PSCAD. Simulation results are shown in Figure 4. The results show that the proposed model has high simulation accuracy.
Based on the above 5-level model system, a 200-level MMC simulation model is built in PSCAD. Detailed model simulation takes too long to compare experiments. The experimental results are shown in Figure 5. The proposed model can achieve simulation equivalence, ensure the stability of the output voltage of each sub-module, and greatly improve the simulation efficiency. The simulation time is 63s. The model can meet the simulation speed requirements.

In Figure 6, the speed of the detailed model is compared with the proposed model. The comparison results reflect the rapidity of the proposed model.
5. Conclusion
This paper presents an MMC electromagnetic transient equivalent modeling method. This method realizes the dimensionality reduction of the admittance matrix of the system and greatly improves the simulation speed. At the same time, it ensure high simulation accuracy. This method enables accurate and fast simulations.

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