Fast Energy Equivalent Modeling of MMC Based on Controlled Source

Jiyu Li1, Xue Chen1, DaCai Chen1, Xiangman Ye2, Jintao Guo3 and Zhiwei Cheng3

1State Grid Fujian Economic Research Institute, Fuzhou, China
2Fujian Yongfu Power Engineering Co., Ltd, Fuzhou, China
3State Grid Fujian Maintenance Company, Fuzhou, China

*Corresponding author: li_jiyu@fj.sgcc.com.cn

Abstract. The electromagnetic transient simulation of large-scale MMC has the problems of large memory requirements and long simulation time, which restricts the development of simulation research [1-3]. To solve the problem of low efficiency of MMC electromagnetic transient simulation, this paper proposes a fast energy equivalent model for the equivalent of MMC. Thus, the fast simulation of MMC under normal working conditions and efficiency of simulation model can be realized. First of all, the rationality of achieving the Norton equivalent of MMC bridge arms is derived from the node voltage analysis method. Then the equivalent modeling method of MMC controlled source can be obtained. On this basis, a fast energy equivalent model that can simulate the capacitance characteristics of each sub-module of MMC is proposed by analyzing the switching function form of MMC. Finally, the proposed simulation modeling method was verified on the PSCAD/EMTDC simulation platform.

Keywords: Electromagnetic transient simulation, equivalent model, energy equivalent.

1. Introduction
The DC transmission with thyristor as the converter device is called the Line Commutated Converter High Voltage Direct Current Transmission (LCC-HVDC) technology [4-5]. LCC-HVDC has incomparable advantages over traditional high-voltage AC transmission. Since the new topology of Modular Multilevel Converter (MMC) was proposed, it has been widely used in DC transmission projects [6]. In order to solve the problem of MMC simulation modeling, many scholars have carried out extensive research work. Literature [6-8] introduce some MMC real-time simulation modeling methods. However, the real-time simulation models require more specific hardware configurations. Literature [9] propose a method to determine whether the model can retain the status update of the capacitor voltage of each sub-module as a judgment condition. Literature [10, 11] use controlled voltage source and controlled current source to realize the electrical decoupling of bridge arms and sub-module. Through the independent modeling of each sub-module, the dimensionality reduction of the admittance matrix is realized, thereby improving the simulation efficiency. Literature [13] use interpolation prediction and advanced prediction methods to compensate for the problem of errors
caused by electrical signal transmission lag. However, this simulation model also forms a large number of sub-loops and still contains a large number of nonlinear components, which is not suitable for large-scale simulation analysis. To solve the problem of low efficiency of MMC electromagnetic transient simulation, this paper proposes a fast energy equivalent model for the equivalent of MMC bridge arms and sub-modules.

2. Another section of your paper Modeling method based on controlled source

2.1. Equivalent theoretical analysis

The basic topology of three-phase MMC is shown in Figure 1. MMC is composed of a total of 6 arms in three phases. The total number of input sub-modules for the upper and lower arm of each phase unit is \( N \) in order to keep the stability of the DC bus voltage \( U_{DC} \).

![Fig. 1 Topological structure diagram of three-phase MMC](image)

Using the nodal voltage analysis method, the nodal admittance matrix of each arm can be obtained, as shown in (1) [14].

\[
\begin{bmatrix}
J_1 \\
J_2 - J_1 \\
\vdots \\
J_N
\end{bmatrix}
= \begin{bmatrix}
Y_{11} & Y_{12} & \cdots & \\
Y_{21} & Y_{22} & \cdots & \\
\vdots & \vdots & \ddots & \\
Y_{N(N-1)} & Y_{NN}
\end{bmatrix}
\begin{bmatrix}
U_1 \\
U_2 \\
\vdots \\
U_N
\end{bmatrix}
\]

\( (1) \)

Where, \( U_k (1 \leq k \leq N) \) represents the node voltage of each node. The expression of \( U_k \) is shown in (2).

\[
U_k = J_k R_k + J_{k+1} R_{k+1} + \cdots + J_{N-1} R_{N-1} + J_N R_N
\]

\( (2) \)

Define the equivalent resistance \( R_{eq} \), equivalent admittance \( Y_{eq} \) and equivalent current source \( J_{eq} \) of the arm:

\[
R_{eq} = \sum_{k=1}^{N} R_k \quad Y_{eq} = \frac{1}{\sum_{k=1}^{N} R_k} \quad J_{eq} = \frac{\sum_{k=1}^{N} J_k R_k}{\sum_{k=1}^{N} R_k}
\]

\( (3) \)
The output voltage $U_{SMk}$ of the MMC sub-module can be expressed as:

$$U_{SMk} = J_k R_k = U_k - U_{k+1} (1 \leq k \leq N)$$

### 2.2. Controlled source equivalent modeling

Based on the analysis of the above controlled source equivalent theory, an equivalent modeling method based on the controlled source MMC can be obtained. The controlled source equivalent model is equivalent to the arm and sub-modules respectively for retaining the coupling of the secondary information [15]. In this way, the cascade of a large number of switching devices is avoided, and the dimension reduction of the nodal admittance matrix of the simulation modeling process is realized.

Through the above modeling steps, the controlled source equivalent modeling of the MMC arm is realized. At the same time, the implementation of this method does not change the structure of the sub-module, and the simulation modeling can be realized by using the original components of the simulation platform. However, this method brings a large number of sub-loops in the model, which still contains a large number of nonlinear components and it is not convenient to carry out high-level simulation.

### 3. Organization of the Text Energy equivalent modeling process

The controlled source equivalent modeling method realizes the dimensionality reduction of the node admittance matrix of the MMC system. In order to further simplify the circuit, the energy equivalent modeling is carried out according to the independent sub-module. The specific equivalent process of Energy Equivalent Submodule (EESM) can be divided into two parts: MMC switching function equivalent and energy equivalent modeling.

#### 3.1. MMC switch function

In the normal working state, each sub-module of the bridge arm is switched on and off according to the control signal, which can ideally simplify the on and off process of the sub-module switch tube to a switching function.

Since the bridge arm voltage is the superposition of the voltages of the sub-modules, it can be seen that the phase A upper bridge arm voltage $U_{RM_PA}$ and the lower bridge arm voltage $U_{RM_NA}$ can be expressed as:
3.2. Energy equivalent modeling

Based on the ideal simplification of sub-module switching devices, this paper proposes to update the capacitor voltage by using the method of conservation of input and output energy of the sub-module capacitor.

Formula (7) can get the sub-module energy change $\Delta E_{SM}$ at the current moment, $\Delta E_{SM}$ is related to the sub-module capacitor voltage $U_c$ at the previous time and the capacitor branch current $I_c$.

$$
\begin{align*}
I_c(t-\Delta t) & = I_{RM,PA}(t-\Delta t)S_k(t-\Delta t) \\
\Delta E_{SM}(t) & = U_c(t-\Delta t)I_c(t-\Delta t)\Delta t
\end{align*}
$$

(7)

The energy storage change of the sub-module capacitance is $\Delta E_c$. $\Delta E_c$ can be obtained by (8):

$$
U_c(t) = \sqrt{\frac{2\Delta E_c(t)}{C} + U_c^2(t-\Delta t)}
$$

(8)

Due to the simplification of the switch, the energy change of the sub-module at the current moment will be converted into the energy change of the sub-module capacitance, which can be expressed as (9):

$$
\Delta E_c(t) = \Delta E_{SM}(t)
$$

(9)

Combine (7), (8) and (9), $U_c(t)$ can be calculated as (10):

$$
U_c(t) = \sqrt{\frac{2U_c(t-\Delta t)I_c(t-\Delta t)\Delta t}{C} + U_c^2(t-\Delta t)}
$$

(10)

It can be seen from (10) that the advantage of using energy equivalent calculation is that the capacitor voltage value in the electromagnetic transient simulation is only related to the capacitor voltage and current at the previous moment.

According to the symmetrical characteristics of the MMC three-phase structure, the three-phase MMC fast energy equivalent model can be established from the above equivalent process. Figure 3 shows the three-phase MMC fast energy equivalent model.
The energy equivalent modeling of MMC through the above-mentioned method is characterized by the use of the overall output voltage of the equivalent MMC bridge arm of the voltage-controlled source to achieve consistent MMC output characteristics. At the same time, the dimensionality reduction of the high-order admittance matrix of the original system is completed.

4. Conclusions Simulation modeling analysis
This paper constructs the simulation based on the control system structure of MMC simulation. According to the proposed MMC fast energy equivalent modeling method, the traditional model, the controlled source equivalent model and the fast energy equivalent model are compared and analyzed on the PSCAD/EMTDC simulation platform.

4.1. Energy equivalent modeling
From the operating principle of the MMC system, it can be known that MMC can achieve direct current control by establishing a mathematical model in a synchronous rotating coordinate system. Considering that the NLM modulation method has more technical advantages in high-level simulation, this article will introduce the control system with the NLM modulation method.

4.2. Verification of simulation accuracy
In order to verify the effectiveness of the MMC fast energy equivalent model, a 21-level bipolar MMC-HVDC simulation model was built on the PSCAD/EMTDC simulation platform, as shown in Figure 8.
Fig. 5 21-level bipolar MMC-HVDC system structure diagram

Table. 1 MMC-HVDC model system parameters

| Parameter                              | Value               |
|----------------------------------------|---------------------|
| AC side voltage                        | 230kV               |
| frequency                              | 50Hz                |
| Transformer rated capacity             | 530MVA              |
| Transformer rated transformation ratio | 230kV/166.57kV(Y/Δ) |
| DC side voltage                        | ±320kV              |
| Bridge arms reactor                    | 60mH                |
| Number of sub-modules                  | 480(120×4)          |
| Sub-module capacitance value           | 10000μF             |

4.2.1. Model accuracy verification. The simulation accuracy of the proposed fast energy equivalent modeling method is verified by observing and comparing the operating characteristics of the MMC model in a steady-state environment.

Fig. 6 MMC model operating characteristics

(a) The capacitor voltage of the first sub-module of the A-phase upper arm of MMC1

(b) A phase upper arm current of MMC1

(c) Output voltage of A phase upper arm of MMC1
It can be seen from the comparison in Fig. 6 that the sub-module capacitance voltage, bridge arm current, and bridge arm voltage of the proposed model have a high degree of fitting with the detailed model, showing good steady-state simulation accuracy. The bridge arm voltage waveform is stable, indicating that the proposed model can respond well to the control of the modulation strategy. Further, the quantitative analysis of the model error is performed on the data in Figure 6 to obtain the proposed model error percentage, as shown in Table 2.

Table 2 Model comparison error percentage

| Corresponding simulation diagram | Parameter               | Error % |
|----------------------------------|-------------------------|---------|
| Fig.6 (a)                        | Sub-module capacitor voltage | 0.074  |
| Fig.6 (b)                        | A phase upper arm current  | 1.67    |
| Fig.6 (c)                        | A phase upper arm output voltage | 0.94   |

4.2.2. System power step verification. The stability of the MMC-HVDC bipolar system shown in Fig. 5 is simulated and compared, as shown in Fig. 7.

It can be seen from Figure 7 that when the transmission power changes suddenly, the model proposed in this paper can respond in accordance with the traditional model. The output voltage on the DC side fluctuates slightly upwards and then returns. The active power is quickly adjusted to near the set value, and then gradually approaches the set value, and the reactive power remains basically constant.

5. Conclusions

This paper proposes a fast energy equivalent electromagnetic transient simulation model of MMC, which solves the contradiction between high efficiency and high accuracy of the traditional equivalent model in a high-level environment. The process of establishing a fast energy equivalent model in the PSCAD/EMTDC is introduced, and the fast energy equivalent model proposed in this chapter has the following characteristics:
(1) The bridge arm and the sub-module are independent of each other in electrical structure, and the coupling of the secondary information is retained, and the energy is equivalent for the sub-module.

(2) Put forward new ideas for capacitor voltage update. Starting from the principle of equivalent circuit energy of the sub-module, calculate the sub-module capacitor voltage update. The principal logic is fresh, the method is simple to implement, and the model application is reliable.

(3) The simulation equivalent model realizes the dimensionality reduction of the nodal admittance matrix of the whole circuit, and simplifies a large number of non-linear components, realizes high-efficiency and high-precision simulation, and can be applied to the simulation research of large-scale flexible DC transmission.

References
[1] Debnath S , Qin J , Bahrami B. Operation, Control, and Applications of the Modular Multilevel Converter: A Review [J]. IEEE Transactions on Power Electronics, 2015, 30(1):37-53.
[2] Marquardt R . Modular Multilevel Converter topologies with DC-Short circuit current limitation [J]. 2011, 13(2):13-15.
[3] Marquardt R. Modular Multilevel Converter: An universal concept for HVDC-Networks and extended DC-Bus-applications [C] Power Electronics Conference (IPEC), 2010 International. IEEE, 2010.
[4] Q. Tu and Z. Xu, Impact of Sampling Frequency on Harmonic Distortion for Modular Multilevel Converter [J]. IEEE Transactions on Power Delivery, 2011, 26(1):298-306.
[5] Ilves K , Antonopoulos A , Norrga S. A New Modulation Method for the Modular Multilevel Converter Allowing Fundamental Switching Frequency [J]. IEEE Transactions on Power Electronics, 2012, 27(8):991-998.
[6] Song Q, Liu W, Li X. A Steady-State Analysis Method for a Modular Multilevel Converter [J]. IEEE Transactions on Power Electronics, 2013, 28(8): 3702-3713.
[7] Solas E, Abad G, Barrena J A. Modular Multilevel Converter With Different Submodule Concepts—Part I: Capacitor Voltage Balancing Method [J]. IEEE Transactions on Industrial Electronics, 2013, 60(10):4525-4535.
[8] Bergna G, Berne E, Egrot P. An Energy-Based Controller for HVDC Modular Multilevel Converter in Decoupled Double Synchronous Reference Frame for Voltage Oscillation Reduction [J]. IEEE Transactions on Industrial Electronics, 2013, 60(6): 2360-2371.
[9] Antonopoulos A, Angquist L , Norrga S. Modular Multilevel Converter AC Motor Drives With Constant Torque From Zero to Nominal Speed [J]. IEEE Transactions on Industry Applications, 2014, 50(3):1982-1993.
[10] Tu Q , Xu Z , Huang H. Parameter design principle of the arm inductor in modular multilevel converter based HVDC [C]. International Conference on Power System Technology. 2010.
[11] Zhang M , Huang L, Yao W. Circulating Harmonic Current Elimination of a CPS-PWM-Based Modular Multilevel Converter With a Plug-In Repetitive Controller [J]. IEEE Transactions on Power Electronics, 2013, 29(4):2083-2097.
[12] P. M. Meshram and V. B. Borghate. A Simplified Nearest Level Control (NLC) Voltage Balancing Method for Modular Multilevel Converter (MMC) [J]. IEEE Transactions on Power Electronics, 2014, 30(10): 450-462.
[13] Liang G, Tafti H D, Farivar G. Analytical Derivation of Inter-Submodule Active Power Disparity Limits in Modular Multilevel Converter-Based Battery Energy Storage Systems [J]. IEEE Transactions on Power Electronics, 2020, 12(99):1-1.
[14] Yang H , Saecidifard M, Yazdani A. An Enhanced Closed-loop Control Strategy with Capacitor Voltage Elevation for the DC-DC Modular Multilevel Converter [J]. IEEE Transactions on Industrial Electronics, 2019, 34(3):2366-2375.
[15] Zhang, Xiaotian, Wang. A Push–Pull Modular-Multilevel-Converter-Based Low Step-Up Ratio DC Transformer [J]. IEEE Transactions on Industrial Electronics, 2019, 66(3):2247-2256.