Research on real time simulation modeling method of large scale MMC electromagnetic transient

Lei Wang¹, Hongjun Zhang¹, Hui Hu¹, Liping Hao¹, and Wei Xu²*

¹Liupanshui Power Supply Bureau of Guizhou Power Grid Co., Ltd., Liupanshui, Guizhou, 553000, China
²Shanghai YISU Information Technologies Co., Ltd., Minhang, Shanghai, 201100, China
*Corresponding author’s e-mail: wei.xu@yisuworld.com

Abstract. Modular multilevel converter (MMC) contains a large number of power electronic switching devices. The modeling method based on switching circuit model needs a lot of resources and the simulation speed is slow, so it is difficult to realize large-scale real-time simulation of electromagnetic transient. A MMC electromagnetic transient numerical modeling method based on ideal transformer model (ITM) is presented. Firstly, the MMC system is divided into the main circuit network and the sub module group network by ITM method, and the error caused by decoupling delay in serial and parallel real time simulation is compensated respectively by interpolation prediction and advanced interpolation prediction. Secondly, the capacitor in sub module is discreted respectively by trapezoidal integration method, backward Euler method and Gear-2 method. Based on the above numerical integration, the difference equations of capacitance voltage, capacitance current and output voltage of half bridge and full bridge sub modules are derived. Then, in order to improve the calculation speed, a simplified numerical model of half bridge and full bridge sub module based on switching function is proposed. Finally, the MMC based on switching circuit model runs off-line simulation in the simulation software, and the above MMC numerical modeling method runs real-time simulation in Speedgoat real-time simulator. The off-line and real-time simulation results of the MMC numerical modeling method and the switching circuit model are compared. And the simulation results verify the feasibility and effectiveness of the above MMC numerical modeling method in real time simulation.

1. Introduction
Modular multilevel converter (MMC) has been applied in the field of flexible DC transmission due to its advantages of unbalanced operation, fault ride through ability and low switching loss. But in practical engineering application, it is usually necessary to test and verify the feasibility and effectiveness of its hardware equipment and control system. Among them, hardware in loop test is an efficient test method to verify the control protection strategy, which requires that the electromagnetic transient simulation of the main circuit including MMC can achieve synchronization with the real clock. However, MMC has a large number of power electronic switch devices. If traditional modeling method based on switching circuit is adopted, it will be difficult to simulate in real-time mode. At present, most literatures have proposed modeling methods for MMC high efficiency electromagnetic transient simulation, such as Thevenin equivalent model of MMC bridge arm unit [6-8], MMC average model [9-11], L/RC model of MMC sub module [12] and electrical order reduction
decoupling model [13]. These methods can improve the real-time simulation modeling of MMC. For example, literature [14] based on literature [8] adopts backward Euler method to equivalent the arm unit of MMC bridge with Thevenin, and realizes the real-time simulation of 601 levels MMC system based on RT-LAB platform.

At present, the commercial simulation platform which can realize the real-time simulation of MMC electromagnetic transient is mainly RT-LAB and RTDS. Among them, RT-LAB has launched MMC HVDC hardware in kind simulation solution earlier than RTDS. Both of them are real-time simulation modeling of valve body by FPGA, but for the same number of modules, RTDS needs more FPGA resources than RT-LAB. The state space node algorithm used by RT-LAB needs to calculate the equivalent circuits of Thevenin or Norton of each partition network in advance. The general program of equivalent circuit pre calculation and overall circuit solution is difficult to realize. The interface algorithm of transmission line model adopted by RTDS needs to adjust the parameter value of additional circuit according to different circuit parameters [16]. And the valve control circuit based on L/RC model needs a small simulation step, so it is not suitable for multi CPU core parallel simulation. On the other hand, RT-LAB and RTDS are commercial real-time simulation platforms, and their hardware configuration costs are more expensive, and the cost of later expansion and upgrading is also high.

In this paper, a real-time simulation numerical modeling method based on ideal transformer model method (ITM) is proposed. The detailed description and derivation of the method are given in detail from the circuit segmentation principle, error compensation of circuit decoupling delay, detailed and simplified numerical modeling principle of half bridge and full bridge sub module. In the aspect of simulation analysis, firstly, taking 21 level MMC inverter as an example, the accuracy of serial simulation is compared with the MMC segmentation model based on several interpolation prediction; Then, taking the full bridge sub module as an example, the simulation accuracy and acceleration effect of the sub module based on several discrete methods are compared; Finally, taking 21 level half bridge MMC flexible distribution system as an example, the simulation of MMC multi-core parallel simulation based on the above modeling principle is compared with the original overall circuit model in power flow regulation and uninterruptible power supply.

2. Equivalent model of MMC based on ITM

2.1. Circuit model segmentation of MMC based on ITM

Circuit model segmentation is based on the idea of grouping, which can divide a higher order power system network into several lower order independent sub networks. The interface algorithms between the associated networks mainly include: node splitting method, state space nodal (SSN), damping impedance method (DIM) and ideal transformer model method (ITM) [17]. The node splitting method and SSN algorithm need to pre-process each sub network with Thevenin equivalent or Norton equivalent. The dim method and ITM method both use controlled source to replace the associated sub network to realize the simultaneous operation simulation of the whole network. The dim method has higher stability region and simulation accuracy than the ITM method, but when the circuit parameters change, the dim method needs to reset the impedance parameters. For the convenience of implementation, ITM method is used to segment the circuit model of cascaded MMC, as shown in Figure 1.

In fact, because of circuit decoupling, in order to avoid the algebraic loop between the main network and the sub network, it is necessary to insert the delay unit between the voltage and current signal in series simulation mode. The decoupling delay unit will cause the capacitor voltage of MMC segmentation model to lose control under some circuit parameters, and then lead to serious instability of MMC output waveform.
2.2. Error compensation method of MMC segmentation model

In this paper, the interpolation prediction method is used to compensate the error caused by the delay unit, and the next step electric quantity is interpolated and extrapolated according to the historical value. The common interpolation extrapolation methods include flat wave interpolation, least square method, linear interpolation, and parabolic interpolation. The basic principle is shown in figure 2. Among them, the flat wave prediction interpolation has the same slope as the least square method, which is mainly used for armature current prediction in BPA version of EMTP. Linear interpolation is used to predict angular velocity in BPA of EMTP. Parabolic interpolation can be regarded as the prediction based on the slope change rate (second order derivative) of two lines formed by adjacent historical points. Because the above interpolation extrapolation methods use the first few step history values for prediction, the prediction effect of discrete variables with mutation characteristics is not ideal, so the last step history value can be directly used for such variables or mutation points.

![Fig. 2 Several interpolation extrapolation methods](image)

The corresponding interpolation formulas in the figure above are as follows:

\[ i'(t) = \frac{5}{4} i(t - \Delta t) + \frac{1}{2} i(t - 2\Delta t) - \frac{3}{4} i(t - 3\Delta t) \]  \hspace{1cm} (1)

\[ i'(t) = \frac{4}{3} i(t - \Delta t) + \frac{1}{3} i(t - 2\Delta t) - \frac{2}{3} i(t - 3\Delta t) \]  \hspace{1cm} (2)

\[ i'(t) = 2i(t - \Delta t) - i(t - 2\Delta t) \]  \hspace{1cm} (3)

\[ i'(t) = 3i(t - \Delta t) - 3i(t - 2\Delta t) + i(t - 3\Delta t) \]  \hspace{1cm} (4)
When the single core serial simulation is used, the output voltage of the sub module is not suitable for interpolation prediction because of the sudden change of the output voltage, and the waveform of the bridge arm current is relatively smooth due to the existence of the bridge arm reactor. In order to solve the algebraic loop problem between the main network and the sub network, the delay unit is added to the current channel of the bridge arm to make interpolation prediction, and the output voltage of the sub module directly uses the present value.

When multi-core parallel simulation is used, if the main network and sub module groups are respectively configured in different CPU cores, there is a fixed delay between CPU cores, which makes the bridge arm current and sub module output voltage channel have one delay. Therefore, the bridge arm current can be compensated by the advanced interpolation prediction method, while the output voltage of the sub module directly uses the historical value of the previous step, and the voltage delay is indirectly compensated [18]. For example, in the calculation results of formula (1) and formula (2), the leading interpolation prediction formulas obtained by using the corresponding interpolation prediction are

\[
i''(t) = \frac{33}{16}i(t-\Delta t) - \frac{1}{8}i(t-2\Delta t) - \frac{15}{16}i(t-3\Delta t)
\]

(5)

\[
i'(t) = \frac{19}{9}i(t-\Delta t) - \frac{2}{9}i(t-2\Delta t) - \frac{8}{9}i(t-3\Delta t)
\]

(6)

Electromagnetic transient numerical model of sub module network

After the MMC model is segmented by ITM method, the electrical decoupling between each sub module is realized. In addition, the output voltage and capacitor voltage signals of each sub module are only needed when the main network and sub module groups operate simultaneously. Therefore, the electromagnetic transient value of each sub module network can be directly established, and the difference equations of the above related variables of each sub module can be directly solved in order to facilitate the efficient operation of MMC real-time simulation.

2.3. Discretization of sub module capacitor

For the electromagnetic transient simulation of MMC sub module network, it is necessary to discretize the capacitor elements in the sub module. The commonly used discretization methods are trapezoidal integral method (A-stability), backward Euler method (A-stability), gear-2 method (A-stability), Simpson method (conditional stability) and Runge Kutta method (conditional stability). In this paper, the trapezoidal integral method, backward Euler method and gear-2 method are selected to discretize the capacitor elements in the sub module. The volt ampere characteristics of the capacitor are as follows

\[
u_c(t) = u_c(t-\Delta t) + \frac{1}{C} \int_{t}^{t+\Delta t} i_c(t)dt
\]

(7)

If trapezoidal integral method is adopted, the expression of capacitive current can be obtained from equation (7)

\[
i_c(t) = \frac{2C}{\Delta t}u_c(t) - \frac{2C}{\Delta t}u_c(t-\Delta t) - i_c(t-\Delta t)
\]

(8)

If backward Euler method is adopted, the expression of capacitive current can be obtained from equation (7)

\[
i_c(t) = \frac{C}{\Delta t}u_c(t) - \frac{C}{\Delta t}u_c(t-\Delta t)
\]

(9)

If gear-2 method is adopted, the expression of capacitive current can be obtained from equation (7)

\[
i_c(t) = \frac{3C}{2\Delta t}u_c(t) - \frac{2C}{\Delta t}u_c(t-\Delta t) + \frac{C}{2\Delta t}u_c(t-2\Delta t)
\]

(10)
In order to facilitate the derivation and expression of the sub module numerical model based on the above three numerical integration methods, equation (8), equation (9) and equation (10) can be written into the following unified Norton equivalent form:

$$i_C(t) = u_C(t)/R_C + I_{Ch}$$  \hspace{1cm} (11)

Where, $R_C$ is the equivalent resistance of the capacitor; $I_{Ch}$ is current history terms. The specific value of $R_C$ and $I_{Ch}$ is determined by the discretization method

$$R_C = \begin{cases} \\
\frac{dt}{2C} & \text{trapezoidal} \\
\frac{dt}{C} & \text{backward Euler} \\
\frac{2dt}{C} & \text{Gear-2} \\
\end{cases}$$  \hspace{1cm} (12)

$$I_{Ch} = \begin{cases} \\
-\frac{i_C(t - \Delta t) - 2C}{dt} u_C(t - \Delta t) & \text{trapezoidal} \\
-\frac{C}{dt} u_C(t - \Delta t) & \text{backward Euler} \\
\frac{C}{2dt} u_C(t - 2\Delta t) - \frac{2C}{dt} u_C(t - \Delta t) & \text{Gear-2} \\
\end{cases}$$  \hspace{1cm} (13)

Among the above discretization methods, trapezoidal integration method is widely used in electromagnetic transient simulation of power system because of its good stability and high simulation accuracy, but it may produce numerical oscillation. Although the simulation accuracy of backward Euler method is not as good as trapezoidal integration method, it does not produce numerical oscillation and has a more simplified calculation. When the simulation step is small, the simulation accuracy is acceptable. Gear-2 method does not produce numerical oscillation, and its simulation accuracy is between trapezoidal integration method and backward Euler method.

2.4. Electromagnetic transient numerical model of half bridge sub module

According to equation (11), after the half bridge sub module network is discretized by trapezoidal integration method, backward Euler method or gear-2 method, the electromagnetic transient discrete adjoint circuit has the same form, which can be unified into the circuit structure as shown in Figure 3. The only difference is that capacitor equivalent resistance $R_C$ and current history terms $I_{Ch}$ have different equation, which is equation (12) and equation (13). Therefore, for the half bridge sub module, the electromagnetic transient numerical model based on the above discretization method can be derived and expressed in a unified form.

![Fig. 3 Discrete companion circuit of half bridge module](image)

According to the circuit model in Figure 3, the difference equations of half bridge sub module capacitor voltage $u_C^B(t)$, capacitor current $i_C^B(t)$ and sub module output voltage $u_C^B(t)$ can be derived from KCL equation and VCR equation of each component

$$u_C^B(t) = \frac{R_1R_C}{R_1 + R_2 + R_C} i(t) - \frac{(R_1 + R_2)R_C}{R_1 + R_2 + R_C} I_{Ch}$$  \hspace{1cm} (14)
\[
    i_C^B(t) = \frac{R_x}{R_x + R_z + R_C}i(t) + \frac{R_y}{R_y + R_z + R_C}I_{ch} \tag{15}
\]
\[
    u_C^B(t) = R_z\left(i(t) - i_C^B(t)\right) \tag{16}
\]

Where, the superscript B represents the half bridge MMC sub module, and the capacitance equivalent resistance \(R_z\) and current history term \(I_{ch}\) are determined by the discretization method, and formula (12) and formula (13).

The values \(R_1, R_2\) are determined by their respective trigger pulse States,

\[
    R_i = \begin{cases} R_{on} & S_i = 1 \\ R_{off} & S_i = 0 \end{cases} (i = 1, 2) \tag{17}
\]

Equations (14) - (17) constitute the electromagnetic transient numerical model of half bridge MMC sub module network, and each sub module numerical model is operated independently. The overall equivalent of MMC proposed in reference [6-7] is also based on the ITM segmentation method, which is different from that in this paper. It only splits the main circuit and the overall unit of bridge arm, and then makes the overall equivalent of Thevenin for the unit of bridge arm. In this paper, each sub module is modeled separately, and then the output voltage is summed. But the two are equivalent, because the main circuit only needs the total output voltage of the bridge arm sub module to calculate when it is divided based on the ITM method. However, if Thevenin's integral equivalence is applied to the bridge arm element, the unnecessary summation of concentrated resistance parameters will be increased.

2.5. Electromagnetic transient numerical model of full bridge sub module

Similar to the numerical modeling of half bridge sub module, the electromagnetic transient adjoint circuit of full bridge sub module also has a unified structure after discretization by trapezoidal integral method, backward Euler method or gear-2 method, as shown in Figure 5. The difference is that the values of capacitance equivalent resistance \(R_z\) and current history term \(I_{ch}\) are different.

![Fig. 4 Discrete companion circuit of full bridge module](image)

According to the circuit model in Figure 4, the difference equations of full bridge sub module capacitor voltage \(u_C^F(t)\), capacitor current \(i_C^F(t)\) and sub module output voltage \(u_C^F(t)\) can be derived from KCL equation and VCR equation of each component

\[
    u_C^F(t) = \frac{AR_C}{B + CR_C}i(t) - \frac{BR_C}{B + CR_C}I_{ch} \tag{18}
\]
\[
    i_C^F(t) = \frac{A}{B + CR_C}i(t) + \frac{CR_C}{B + CR_C}I_{ch} \tag{19}
\]
\[
    u_C^F(t) = \frac{E + DR_C}{B + CR_C}i(t) - \frac{AR_C}{B + CR_C}I_{ch} \tag{20}
\]

Where:
\[
A = R_2 R_3 - R_1 R_4 \\
B = R_1 R_3 + R_1 R_4 + R_2 R_3 + R_2 R_4 \\
C = R_0 + R_2 + R_3 + R_4 \\
D = R_1 R_2 + R_1 R_4 + R_2 R_3 + R_3 R_4 \\
E = R_1 R_2 R_3 + R_1 R_2 R_4 + R_1 R_3 R_4 + R_2 R_3 R_4 
\]

Where, the superscript \(F\) represents the full bridge MMC sub module, and the capacitance equivalent resistance \(R_c\) and current history term \(I_{ch}\) are determined by the discretization method, and formula (12) and formula (13).

The values \(R_1, R_2, R_3, R_4\) are determined by their respective trigger pulse States,

\[
R_i = \begin{cases} 
R_{on} & S_i = 1 \\
R_{off} & S_i = 0 
\end{cases} \quad (i = 1, 2, 3, 4) \tag{21}
\]

It is worth noting that: unlike trapezoidal integration method, after discretization by backward Euler method and gear-2 method, the historical term in the difference equation does not include the capacitive current term, and the difference equation of capacitive voltage and sub module output voltage does not need the capacitive current term for iterative calculation. Therefore, when we do not pay attention to the capacitive current of sub module, the difference equation of capacitive current using backward Euler method or gear-2 method can be omitted to reduce the amount of calculation.

3. Simplified numerical model of submodular network

Comparing the numerical models of half bridge and full bridge sub module, it can be seen that the difference equation of full bridge sub module is much more complex than that of half bridge sub module, and its computation is mainly focused on the calculation of the coefficient of difference equation, which will increase the computational burden of processor and limit the scale of real-time simulation of MMC. In this paper, a relatively simplified numerical model of half bridge and full bridge sub modules is proposed, which is suitable for the large-scale real-time simulation of half bridge or full bridge MMC.

3.1. Simplified numerical model of half bridge sub module

According to the control and operation characteristics of the half bridge sub module, the output characteristics of the sub module can be divided into two states: capacitor voltage on and capacitor voltage off. If the conventional switching function method is used for modeling, the stability will be poor due to the decoupling delay between AC and DC networks. Therefore, the sub module DC network can be directly discretized, and the excitation current source can be taken as the switch function of the bridge arm current. The simplified equivalent circuit is shown in Fig. 5.

\[i_c = i^n(t)\]

3.1. Simplified numerical model of half bridge sub module

In Fig. 5 (b), the current source of the injected capacitor is determined by the bridge arm current and the half bridge sub module switching function

\[i^n(t) = S^n i(t)\]

\[S^n = \begin{cases} 
1 & S_1 = 1, S_2 = 0 \\
0 & S_1 = 0, S_2 = 1 
\end{cases} \tag{23}\]
If the trapezoidal integral method is adopted, the difference equation of capacitor voltage in Figure 5 (b) can be deduced as

\[ u_c(t) = u_c(t - \Delta t) + S^u \frac{\Delta t}{2C} \left( i(t) + i(t - \Delta t) \right) \]  

(24)

If the backward Euler method is adopted, the difference equation of capacitor voltage in Figure 5 (b) can be deduced as

\[ u_c(t) = u_c(t - \Delta t) + S^u \frac{\Delta t}{C} i(t) \]  

(25)

If the Gear-2 method is adopted, the difference equation of capacitor voltage in Figure 5 (b) can be deduced as

\[ u_c(t) = \frac{4}{3} u_c(t - \Delta t) - \frac{1}{3} u_c(t - 2\Delta t) + S^u \frac{2\Delta t}{3C} i(t) \]  

(26)

The output voltage of the half bridge sub module is determined by its switching function and capacitor voltage

\[ u_o(t) = S^u u_c(t) \]  

(27)

The basic principle of the simplified half bridge sub module numerical method is to transform the time-varying characteristics of the switching resistance in the sub module circuit model into the time-varying characteristics of the current injected into the capacitor. From the difference equation of the simplified model, it can be seen that the difference of calculation burden between the above discretization methods is small, and the calculation burden based on gear-2 method is the largest.

3.2. Simplified numerical model of full bridge sub module

According to the control and operation characteristics of the full bridge sub module, the simplified equivalent circuit of the similar full bridge sub module is shown in Figure 6. The capacitor switching state has three states: positive input, cut-off and negative input, so the current mode of capacitor injection is different from that of half bridge sub module.

\[ S^F = \begin{cases} 
1 & S_1 = S_3 = 1 \wedge S_2 = S_4 = 0 \\
0 & S_1 = S_3 = 1 \lor S_2 = S_4 = 1 \\
-1 & S_2 = S_3 = 1 \wedge S_1 = S_4 = 0 
\end{cases} \]  

(29)

The capacitor voltage difference equation of full bridge sub module is similar to that of half bridge sub module. For the convenience of comparison with the detailed numerical model, the capacitance voltage difference equation of the simplified model based on trapezoidal integral method, backward Euler method or gear-2 method is unified as the following form

\[ u_c(t) = S^F R_c i(t) + R_c I_{ch} \]  

(30)

Where, \( R_c \) of is the same as that of (12), and \( I_{ch} \) is
The output voltage of the full bridge sub module is determined by its switching function and capacitor voltage

\[ u_c(t) = S^T u_c(t) \]  \hspace{1cm} (32)

Equations (28) - (32) can form a simplified numerical model of full bridge sub module network. Compared with the detailed numerical model, it can be seen that the difference equation coefficients of capacitor voltage and output voltage are much simpler than the detailed numerical model.

However, the simplified full bridge sub module numerical method can also simulate the dynamic characteristics of the capacitors of each sub module, and the amount of calculation is greatly reduced. It is suitable for the real-time simulation of more large-scale full bridge MMC and can realize the real-time simulation verification of capacitor voltage balance.

4. Analysis of simulation example

The hardware platform used for example analysis is Speedgoat real time target machine: the processor of the real-time simulator is Intel Core i7-7700k, the number of cores is 4, the main frequency is 4.20GHz, and the memory is 4GB;

4.1. Comparison of simulation accuracy between detailed and simplified numerical models

Take the numerical model of full bridge sub module as an example. In the simulation software, the detailed and simplified numerical models of full bridge sub module based on trapezoidal integration method, backward Euler method and gear-2 method are modeled and compared with the IGBT circuit model in the simulation software. The test adopts the circuit shown in Figure 4, in which the excitation source adopts the sinusoidal current source with amplitude of 10 A and frequency of 50 Hz, the initial value of capacitor voltage is set to 1 kV, the capacitor is set to 0.005 F, the pulse signal takes a fixed period of 0.0001 s, and the simulation step is set to 50µs. Set 0s-0.0005s interval to adopt forward operation; 0.0005s-0.015s section adopts negative operation; The current source is cut off between 0.015s and 0.002s, but the trigger pulse is given continuously. The simulation results of capacitor voltage, capacitor current and output voltage of sub module based on the above model are shown in Fig. 7 and Fig. 8.

The simulation results of the detailed numerical model show that the detailed numerical model of the full bridge sub module based on trapezoidal integration, backward Euler method or gear-2 method is highly consistent with the simulation results of the circuit model. The simulation results of capacitor voltage and output voltage of sub module are almost the same as that of the circuit model based on trapezoidal integral method, because the circuit model in simulation software is also discretized by trapezoidal method; The simulation accuracy of backward Euler method is low, especially in the simulation results of capacitance voltage, which is mainly shown that the simulation results are less than the other two discrete methods; The simulation accuracy of gear-2 method is between trapezoid integral method and backward Euler method. In a word, the above simulation results are basically in accordance with the truncation error law of the numerical integration method.

The simulation results of the simplified numerical model show that the simplified numerical model of the full bridge sub module based on trapezoidal integral method, backward Euler method or gear-2 method is basically consistent with the simulation results of the circuit model. Compared with the simulation results of detailed numerical model, it can be seen that the capacitor voltage does not charge or discharge slightly, as shown in Fig. 8 (a) amplification part, and the output voltage of its sub module does not drop on the switching element, as shown in Fig. 8 (b) amplification part, which is consistent with the modeling characteristics. In addition, the simplified numerical model based on trapezoidal integral method is closer to the simulation results of the circuit model.
4.2. Comparison of computation efficiency between detailed and simplified values

Taking the numerical model of full bridge sub module as an example, according to section 2.1, using ITM method to segment the MMC model, the electrical decoupling between each sub module is realized, the operation of each sub module is independent of each other. Therefore, the real-time simulation here still uses the test circuit in 4.2. The detailed numerical model simplified numerical model and circuit model are real-time and run in Speedgoat real-time simulator. The real-time simulation step is set to 50µs. For the detailed numerical models of backward Euler method and gear-2 method, the calculation term of capacitive current is omitted here; In view of the small difference in the calculation burden of the simplified numerical model among the above discretization methods, only the acceleration effect based on trapezoidal integral method is listed here. The real-time simulation acceleration effects of the above models are shown in Table 1.

It can be seen from the real-time simulation results that when the number of sub modules is small, the acceleration effect of the detailed numerical models based on several discretization methods has little difference, for example, when simulating 60 sub modules, they only occupy nearly 1/6 of the CPU resources. The simulation of 60 sub module switch circuit model has occupied nearly 4/5 of the CPU resources. This is because the basic framework of state space method is used in circuit model calculation. In real-time operation, the system state matrix and inverse matrix need to be adjusted continuously according to different switch states, so the calculation amount is large. For the numerical model, because it is more direct than the circuit model, it has a good acceleration effect.

When the number of sub modules is large, the switch circuit model cannot run in real-time mode, so the scale of MMC real-time simulation is limited; For the detailed numerical model, the trapezoidal integral method needs to calculate the capacitor current for the difference iteration, so its acceleration effect is slightly lower than that of the backward Euler method and gear-2 method. With the increase of the number of sub modules, the computation efficiency of the backward Euler method and gear-2 method are better; For the simplified numerical model, the calculation of the difference equation is much less than that of the detailed model, so its computation efficiency is the best and it can realize the real-time simulation of large-scale MMC based on the computation efficiency trend of real-time simulation.
Table 1. Computation efficiency comparison of full bridge sub module groups.

| Types of models                  | Execution Time (µs) |
|----------------------------------|---------------------|
|                                  | 60 sub modules      | 120 sub modules | 240 sub modules |
| Switch circuit model             | 40                  | —               | —               |
| Detailed model (trapezoid)       | 8                   | 12              | 20              |
| Detailed model (backward Euler)  | 8                   | 11              | 17              |
| Detailed model (Gear-2)          | 8                   | 11              | 18              |
| Simplified model (trapezoid)     | 6                   | 7               | 9               |

4.3. Comparison of parallel real time simulation based on half bridge MMC

Parallel simulation is one of the development trends of MMC real-time simulation, such as PC cluster, CPU-CPU and CPU-FPGA. In this paper, taking the multi-core parallel simulation as an example, the parallel simulation of MMC segmentation model is compared with the switch circuit model. The simulation object is a 21 level MMC flexible distribution network, and its main circuit structure is shown in Figure 9.

Because of the large number of sub modules based on the switch circuit model, it is difficult to be real-time, so it runs in the offline simulation mode. The MMC segmentation model based on numerical model adopts three core parallel simulation mode. The main circuit and control system are configured in one core, and the sub module group and voltage modulation are evenly configured in the other two CPU cores. Equation (6) is used as the prediction unit, while the MMC sub module adopts the detailed and simplified numerical models based on trapezoidal integral method, and the simulation step is set to 50µs.

In case 1, the active power command of MMC2 changes from 0 to -600kW at 2.5s, and the reactive power command changes from 0 to -300kvar at 3.5s. The simulation results are shown in Figure 10; In case 2, a branch of MMC2 is disconnected due to fault at 3.5s, and the control of MMC2 is changed from PQ control to V/F control in order of uninterruptible supply power for the load. The simulation results are shown in Figure 11.

It can be seen that the simulation results of MMC segmentation model based on advanced prediction and sub module numerical model are basically consistent with the MMC switching circuit model. Different from the serial simulation, the parallel simulation needs to predict the bridge arm current in advance. And the output voltage of the sub module directly uses the value of the previous step, so there is still one delay at the voltage mutation point of the sub module which causes deviation of the simulation results. In addition, compared with the simplified numerical model, the detailed numerical model of the sub module is closer to the switch circuit model in most frequency band. However, the simulation results in Section 5.2 show that the simplified numerical model takes less CPU resources and is more suitable for large-scale MMC real-time simulation.
5. Conclusion

If the scale of MMC real-time simulation is small, the detailed numerical model based on trapezoidal integral method is recommended; if the scale of real-time MMC simulation increase, the detailed numerical model based on gear-2 method or backward Euler method are recommended to enlarge the scale of MMC model; When the above detailed numerical models cannot run in real-time mode, the simplified numerical model based on trapezoidal integral method can be recommended to realize the real-time simulation of larger scale MMC. On the other hand, if the scale of MMC simulation is small, serial simulation based on interpolation prediction is recommended. When the scale of MMC simulation is large, parallel simulation based on advanced interpolation prediction can be used.

Subsequently, the research will focus that the simplified numerical model of MMC run in FPGA, and the parallel real-time simulation step size is no more than 1 µs, which can improve the simulation accuracy and be suitable for large-scale real-time simulation of MMC.

References

[1] Yang X, Lin Z, Zheng Q, et al. (2013) A review of modular multilevel converters [J]. Proceedings of the CSEE, 33(6) : 1-14

[2] Li C,Xie Z,Lin W,et al. (2015) Accurate valve loss calculation method and analyzing platform for medium and high-frequency MMC[J].Proceedings of the CSEE,35(17) :4361-4370(in Chinese).

[3] Wang H,Tang G,He Z, et al. (2015) Power losses calculation of modular multilevel converter[J].Automation of Electric Power Systems,39(2) :112-118(in Chinese).

[4] Kurt F. (2010) Modern HVDC PLUS application of VSC in modular multilevel converter topology[C]/IEEE International Symposium on Industrial Electronics (ISIE). Bari, Italy,2010:3807-3810.

[5] Huang H. (2009) Multilevel voltage-sourced converters for HVDC and FACTS applications[C], Cigre, SC B4 2009 Bergen Colloquium. Bergen, Norway,1-8.
[6] Gnanarathna U N, Gole A M, Jayasinghe Rohitha P. (2011) Efficient modeling of modular multilevel HVDC converters (MMC) on electromagnetic transient simulation programs[J]. IEEE Transactions on Power Delivery, 26(1):316-324.

[7] Wang P, Cui X. (2013) A Time-Domain Equivalent Model of Modular Multilevel Converter and Its Fast Algorithm [J]. Power System Technology, 37(8):2180-2186 (in Chinese).

[8] Saad H, Dufour C, Mahseredjian J, et al. (2013) Real time simulation of MMCs using the state-space nodal approach[C]//The International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada, June 18-20.

[9] Rohner S, Weber J, Bernet S. (2011) Continuous model of modular multilevel converter with experimental verification[C]//Energy Conversion Congress and Exposition. Phoenix, AZ: IEEE:4021-4028.

[10] Guo G, Hu X, Wen J, et al. (2015) A Large-Scale Sub Module Group Based Algorithm for Modeling and High-Speed Simulation of Modular Multilevel Converter[J]. Power System Technology, 39(5):1226-1232 (in Chinese).

[11] Zhou S, Lin W, Yao L, et al. (2015) Generic Averaged Value Models for Two-level VSC and MMC[J]. Automation of Electric Power Systems, 39(12):138-144 (in Chinese).

[12] Kaijian Ou, Trevor M, Bruce Warkentin, et al. (2014) Research and Application of Small Time-step Simulation for MMC VSC-HVDC in RTDS[C]. International Conference on Power System Technology, Oct 20-22, 2014, Chengdu, China:877-882.

[13] Xu J, Zhao C, Liu W. (2013) Accelerated model of ultra-large scale MMC in Electromagnetic transient simulations[J]. Proceedings of the CSEE, 33(10):114-120 (in Chinese).

[14] Xiong Y, Zhao C, Liu Q, et al. (2016) Modeling of Real-time Simulation and Hardware-in-the-loop Experiments for Modular Multilevel Converters[J]. Automation of Electric Power Systems, 40(21):84-89 (in Chinese).

[15] Wang W, Zhu J, Li W, et al. (2015) SSN-Based RT-LAB Simulation of MMC-HVDC System[J]. Southern Power System Technology, 9(6):22-27 (in Chinese).

[16] Sumek E, Rudi W. (2015) Real-Time Performance of FPGA-based MMC Valves for HVDC Systems [C]//IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society, Nov 9-12, Yokohama, Japan: 4506 - 4512.

[17] Yue C, Zhou X, Li R. (2004) Study of parallel approaches to power system electromagnetic transient real-time simulation[J]. Proceedings of the CSEE, 24(12):1-7 (in Chinese).

[18] Zhang H, Hao Z, Chen Z, et al. (2017) Modeling Method for Modular Multilevel Converter in Real Time Simulation [J]. Automation of Electric Power Systems, 41(7):120-126 (in Chinese).