One Curve Embedded Full-Bridge MMC Modeling Method with Detailed Representation of IGBT Characteristics

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Abstract. Modular Multilevel Converter is more and more widely used in high voltage DC transmission system and high power motor drive system. It is a major topological structure for high power AC-DC converter. Due to the large module number, the complex control algorithm, and the high power user’s back ground, the MMC model used for simulation should be as accurate as possible to simulate the details of how MMC works for the dynamic testing of the MMC controller. But so far, there is no sample simulation MMC model which can simulate the switching dynamic process. In this paper, one curve embedded full-bridge MMC modeling method with detailed representation of IGBT characteristics is proposed. This method is based on the switching curve referring and sample circuit calculation, and it is sample for implementation. Based on the simulation comparison test under Matlab/Simulink, the proposed method is proved to be correct.

1. Introduction
For power electronic technology development, simulation is a common method to do the theoretical analysis, in order to reduce the cost caused by technical theory of design defect. Now Modular Multilevel Converter (MMC) is is more and more widely used in the field of high power motor drive and High Voltage DC (HVDC) transmission. It is a major topological structure for high power AC-DC converter. Especially in the field of flexible high voltage DC transmission, MMC is used in Shanghai Nanhui HVDC project [1], Nan’ao three-terminal HVDC project [2], Zhoushan five-terminal HVDC project [3] and Xiamen HVDC project [4]. According to different MMC sub-module’s topology structure, the existing MMC can be divided into three kinds: Half Bridge Sub-Module (HBSM) MMC, Full Bridge Sub-Module (FBSM) MMC and Clamping Double Sub-Module (CDSM) MMC. Due to the large module number, the complex control algorithm, and the high power user’s back ground, the MMC model used for simulation should be as accurate as possible to simulate the details of how MMC works for the dynamic testing of the MMC controller. But so far, MMC simulation modelling is mainly based on the MMC average model [5], controlled source equivalent model [6] and Thevenin's equivalent circuit model [7]. There is no simple simulation MMC model which can simulate the switching dynamic process. The duration of IGBT module switching dynamic process can be only a few microseconds. Therefore, the simulation sample time must be as small as possible for realizing the IGBT switching dynamic process real-time simulation. Considering the contradiction between high computational complexity and processor computation power, for MMC real-time simulation implementation getting such a small simulation sample time is difficult using traditional IGBT...
modeling method, such as Hefner model [8] and Kraus model [9]. In other word, until now, there is no traditional method can satisfy the MMC with IGBT switching dynamic process real-time simulation requirement.

In this paper, for real-time simulation implementation, one curve embedded full-bridge MMC modeling method with detailed representation of IGBT characteristics is proposed. Based on circuit calculation and curve embedded, the designed method can be easily implemented using FPGA to realize the full-bridge MMC real-time simulation.

2. MMC mathematic model
The MMC topology diagram is shown in Figure 1. SMn is the MMC sub-module. The mathematic model of MMC is:

\[ U_x = e_x = \frac{1}{2} L_0 \frac{dx}{dt} \]

\[ L_0 \frac{di_{cirx}}{dt} + u_{cirx} = 0 \]

\[ e_x = \frac{u_{nx} - u_{px}}{2} \]

\[ i_{cirx} = \frac{u_{px} - u_{nx}}{2} \]

\[ u_{cirx} = \frac{u_{px} + u_{nx} - u_{dc}}{2} \]

Where \( x = a, b, c \); \( e_x \) is inside MMC virtual voltage; \( i_{cirx} \) is the inside MMC circle current; and \( u_{cirx} \) is the unbalanced voltage cased by \( i_{cirx} \). \( U_{ra}, U_{rb}, U_{rc} \) is the AC voltage; \( i_{ra}, i_{rb}, i_{rc} \) is the AC current; \( L_0 \) is the bridge arm inductance; \( U_{pa}, U_{pb}, U_{pc} \) is the up bridge arm voltage; \( U_{na}, U_{nb}, U_{nc} \) is the down bridge arm voltage; \( i_{pa}, i_{pb}, i_{pc} \) is the up bridge arm current, \( i_{na}, i_{nb}, i_{nc} \) is the down bridge arm current; \( U_{dc} \) is the DC voltage and \( O \) is the virtual neutral point.

![Figure 1. MMC topology diagram](image1)

3. MMC modelling with IGBT switching characteristic curve embedded

3.1. Work status analysis of full bridge MMC sub-module
The circuit of full bridge MMC sub-module is shown in Figure 2. When MMC sub-module works normally, the output voltage \( u_{sm} \) is only determined by the input current \( i_{sm} \) and the module controlled PWM. Analysis the full bridge module work status can based on the IGBT and diode’s characteristic. Considering the switching dead-time effort, there are 9 kinds of controlled PWM exist when the full bridge sub-module works normally:

\( T_1T_2T_3T_4=1010; T_1T_2T_3T_4=0010; T_1T_2T_3T_4=0110; T_1T_2T_3T_4=1000; T_1T_2T_3T_4=0000; T_1T_2T_3T_4=0100; T_1T_2T_3T_4=1001; T_1T_2T_3T_4=0001; T_1T_2T_3T_4=0101. \)
Furthermore, considering the direction of the input current (the current positive direction is shown as Figure 3), there are 18 kinds of work status need to be analyzed. Figure 3 shows all sub-module equivalent circuit at normal work statuses.

Figure 3. MMC sub-module work equivalent circuit analysis

Numbering every work equivalent circuit of full bridge MMC sub-module as shown in Figure 3, considering the switching dead time effort, the status switching between different working statuses can be several kinds, as shown in Figure 4.
From the full bridge MMC sub-module work equivalent circuit, several conclusions can be got:

- When $i_{sm}>0$, between status1 and status4, status2 and status5, status3 and status6, status9 and status10, the status switching doesn’t change the equivalent circuit, although the controlled PWM changes.

- When $i_{sm}<0$, between status1 and status2, status4 and status5, status7 and status8, status5 and status6, status9 and status10, the status switching doesn’t change the equivalent circuit, although the controlled PWM changes.

- When $i_{sm}>0$, between status1 and status5, status2 and status5, status3 and status6, status9 and status10, status switching caused by the PWM signal is influenced by the IGBT switching characteristic.

- When $i_{sm}<0$, between status1 and status4, status2 and status5, status3 and status6, status9 and status10, status switching caused by the PWM signal is influenced by the IGBT switching characteristic.

- Considering the current frequency is much smaller compared with the sample time (simulation sample time should be less than 1 us), the current changes quite small in one sample time. So when the current $i_{sm}$ changes from $i_{sm}<0$ to $i_{sm}>0$ (or from $i_{sm}>0$ to $i_{sm}<0$), no matter which kind of status switching happens, the IGBT switching characteristic’s effect can be ignored.

Based on the above analysis of full bridge MMC sub-module working status switching, a status switching sign can be defined to make the judgments whether the IGBT switching characteristic curve should be embedded. If the controlled PWM at current sample time can be present as $T_1T_2T_3T_4(k)$, and the controlled PWM at last sample time can be present as $T_1T_2T_3T_4(k-1)$, defining the positive current direction as shown in Figure 2, defining the status switching sign as F, the F can be get as follow:

When $i_{sm}>0$:

$$F = \begin{cases} 3 & T_1T_2T_3T_4(k) = 1010, T_1T_2T_3T_4(k-1) = 1000 \\ 4 & T_1T_2T_3T_4(k) = 1000, T_1T_2T_3T_4(k-1) = 1010 \\ 3 & T_1T_2T_3T_4(k) = 0010, T_1T_2T_3T_4(k-1) = 0000 \\ 4 & T_1T_2T_3T_4(k) = 0000, T_1T_2T_3T_4(k-1) = 0010 \\ 3 & T_1T_2T_3T_4(k) = 0110, T_1T_2T_3T_4(k-1) = 0100 \\ 4 & T_1T_2T_3T_4(k) = 0100, T_1T_2T_3T_4(k-1) = 0110 \\ 1 & T_1T_2T_3T_4(k) = 0010, T_1T_2T_3T_4(k-1) = 0110 \\ 2 & T_1T_2T_3T_4(k) = 0110, T_1T_2T_3T_4(k-1) = 0010 \\ 1 & T_1T_2T_3T_4(k) = 0000, T_1T_2T_3T_4(k-1) = 0100 \\ 2 & T_1T_2T_3T_4(k) = 0100, T_1T_2T_3T_4(k-1) = 0000 \\ 1 & T_1T_2T_3T_4(k) = 0001, T_1T_2T_3T_4(k-1) = 0101 \\ 2 & T_1T_2T_3T_4(k) = 0101, T_1T_2T_3T_4(k-1) = 0001 \\ 0 & \text{else} \end{cases}$$

When $i_{sm}<0$:

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Figure 4. MMC sub-module working status switching analysis.
3.2. IGBT switching characteristic curve embedded full-bridge MMC modeling

After getting F using equation (6) and (7), the mathematic model of full bridge sub-module with IGBT switching characteristic curve embedded can be got as follow:

When F=1 or F=2, and \( i_{sm}>0 \),

\[
\begin{align*}
    i_{c1} &= 0 \\
    l_{d1} &= l_{sm1,s} = l_{sm} - l_{sm1,x} \\
    i_{sm1,x} &= i_{c2} \\
    i_{d2} &= 0 \\
    u_{sm1} &= V_{ce2}(i_{c2})
\end{align*}
\]

When F=1 or F=2, and \( i_{sm}<0 \),

\[
\begin{align*}
    i_{sm1,s} &= i_{c1} \\
    i_{d1} &= 0 \\
    i_{c2} &= 0 \\
    i_{d2} &= -i_{sm1,x} = -(l_{sm} - l_{sm1,s}) \\
    u_{sm1} &= u_c - V_{ce1}(i_{c1})
\end{align*}
\]

When F=3 or F=4, and \( i_{sm}>0 \),

\[
\begin{align*}
    i_{sm2,s} &= i_{c3} \\
    i_{d3} &= 0 \\
    i_{c4} &= 0 \\
    i_{d4} &= -i_{sm2,x} = i_{sm} + i_{sm2,s} \\
    u_{sm2} &= u_c - V_{ce3}(i_{c3})
\end{align*}
\]

When F=3 or F=4, and \( i_{sm}<0 \),

\[
\begin{align*}
    i_{c3} &= 0 \\
    i_{d3} &= i_{sm2,s} = i_{sm} - i_{sm2,x} \\
    i_{sm2,x} &= i_{c4} \\
    i_{d4} &= 0 \\
    u_{sm2} &= V_{ce4}(i_{c4})
\end{align*}
\]

In which, \( V_{ce}(i_c) \) is the IGBT switching characteristic curve.

After full bridge sub-module calculation, using the equation (1) ~ (5), IGBT switching characteristic curve embedded full-bridge MMC model is built.

4. Simulation verifying based on Matlab/Simulink

Based on the proposed IGBT switching characteristic curve embedded full-bridge MMC model, using Matlab/Simulink build a simulation model to verify the model’s correction, as shown as Figure 5:
Figure 5. Curve embedded MMC model

Build a comparison full-bridge MMC model based on Matlab/simPowerSystem to compare the simulation result. Using an ideal step curve as the IGBT switching characteristic curve, compare simulation result between the proposed model and the Matlab/simPowerSystem model; Setting the simulation sample time as 200ns, the result is shown as Figure 6. It can be seen in Figure 6 that, using an ideal step curve as the IGBT switching characteristic curve, the simulation result got from both model is same.

Figure 6. Test results comparison

Using the measured IGBT switching characteristic curve as shown in Figure 1, based on the proposed IGBT switching characteristic curve embedded full-bridge MMC model, a simulation result which can present the switching characteristic can be get as Figure7.
5. Conclusion

In this paper, one curve embedded full-bridge MMC modeling method with detailed representation of IGBT characteristics is proposed. Based on circuit calculation and curve embedded, the designed method can be simple. The proposed model can satisfy the requirement of real-time simulation. From the comparison simulation between the proposed model and the Matlab/simPowerSystem model, it proves that, the proposed method is correct.

References

[1] Tang Guangfu. VSC-HVDC technology [M]. Peking: China Electric Power Press, 2010: 30-36(in Chinese).
[2] Chen Ming, Rao Hong, Li Licheng, et al. Analysis on the main wiring of Nan’ao VSC-HVDC transmission system[J].Southern Power System Technology,2012(6):1-5(in Chinese).
[3] Zhou Hao, Shen Yang, Li Min, et al. Research on insulation coordination for converter stations of Zhoushan multi-terminal VSC-HVDC transmission project [J]. Power System Technology,2013,37(4):879-890(in Chinese).
[4] Ma Weiming, Wu Fangjie, Yang Yiming, et al. Flexible HVDC transmission technology’s today and tomorrow [J]. High Voltage Engineering,2014,40(8):2429-2439(in Chinese).
[5] Dennetière S, Nguefeu S, Saad H, et al. Modelling of modular multilevel converters for the France-Spain link [J]. Star, 2013, 2(3): 4.
[6] Xu J, Zhao C, Liu W, et al. Accelerated model of modular multilevel converters in PSCAD/EMTDC[J]. Power Delivery, IEEE Transactions on, 2013, 28(1): 129-136.
[7] Li W, Gregoire L, Sisou Belanger J. An FPGA-based real-time simulator for HIL testing of modular multilevel converter controller [C]. 2014 IEEE Energy Conversion Congress and Exposition. Pittsburgh, USA, 2014.
[8] A. Hefner, and D. Blackburn, An analytical model for the steady status and transient characteristics of the power insulated-gate bipolar transistor [J]. Solid Status Electronics, vol. 31, no. 10, pp. 1513-1532, Oct 1988.
[9] R. Kraus and K. Hoffmann, An analytical model of IGBTs with low emitter efficiency [C], ISPSD93, Monterey CA, vol. 3, pp. 30-34.