IGBT Switching Characteristic Curve Embedded Half-Bridge MMC Modelling and Real Time Simulation Realization

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Abstract. The Modular Multilevel Converter (MMC) is one of the most attractive topologies in recent years for medium or high voltage industrial applications, such as high voltage dc transmission (HVDC) and medium voltage varying speed motor drive. The wide adoption of MMCs in industry is mainly due to its flexible expandability, transformer-less configuration, common dc bus, high reliability from redundancy, and so on. But, when the sub module number of MMC is more, the test of MMC controller will cost more time and effort. Hardware in the loop test based on real time simulator will save a lot of time and money caused by the MMC test. And due to the flexible of HIL, it becomes more and more popular in the industry area. The MMC modelling method remains an important issue for the MMC HIL test. Specifically, the VSC model should realistically reflect the nonlinear device switching characteristics, switching and conduction losses, tailing current, and diode reverse recovery behaviour of a realistic converter. In this paper, an IGBT switching characteristic curve embedded half-bridge MMC modelling method is proposed. This method is based on the switching curve referring and sample circuit calculation, and it is sample for implementation. Based on the proposed method, a FPGA real time simulation is carried out with 200ns sample time. The real time simulation results show the proposed method is correct.

1. Introduction
Nowadays, in the field of high voltage DC transmission [1] and high power motor driven [2], modular multilevel converter (MMC) have been widely used. The wide adoption of MMCs in industry is mainly due to its flexible expandability, transformer-less configuration, common dc bus, high reliability from redundancy, and so on. However, due to the complex MMC topology structure, especially with high MMC level, a MMC control experiment always cost a lot of time and money. Hardware in the loop (HIL) real time simulation is considered as an effective way which can save time and money cost during controllers test, and it is widely used in the field of Aerospace [3], automotive electronic [4], high-speed railway [5] and electric power system [6]. When doing the MMC HIL real time simulation, the most important issue is set up the MMC model. Especially when there is a requirement that the MMC model can show the IGBT switching characteristic, setting up the MMC model becomes more difficult. Now, although the widely used real time simulators such as RTDS and RT_LAB are based well acknowledged simulation software (such as PSCAD and MATLAB), there is no half bridge MMC model with IGBT switching characteristic curve embedded supplied. The well acknowledged IGBT switching characteristic model is Hefner model [7] and Kraus model [8]. These
two models are used in SABER and SPICE or off-line 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 very difficult using Hefner model and Kraus model.

In this paper, for real-time simulation implementation, an IGBT switching characteristic curve embedded half-bridge MMC modeling method is proposed. Based on circuit calculation and curve embedded, the designed method can be easily implemented using FPGA to realize the half-bridge MMC real-time simulation. Based on the proposed model, an FPGA real time simulation experiment with 200ns sample time is carried out to prove the model is correct.

2. IGBT switching characteristic curve

There are several experiment circuits to measure the IGBT switching characteristic curves, and the measurement of the relevant electrical characteristics of the IGBT includes the turn-on and turn-off switching characteristics. Both IGBT turn-on characteristic curves and IGBT turn-off characteristic curves contain 4 kind curves: collector-emitter voltage of IGBT $V_{ce}$, IGBT current $i_c$, IGBT gate voltage $V_{ge}$ and IGBT gate current $i_g$. Fig 1 shows the typical turn-on and turn-off characteristics curves of an IGBT along with the switching time definitions. Fig 1(a) plots the experimental data obtained for the turn-on transient. It can be seen that there is an initial delay between the instant when the gate voltage $V_{ce}$ turns on and the instant when the IGBT current $i_c$ starts to increase (or $V_{ce}$ starts to decrease). After this delay $i_c$ increases to its peak value before settling to its steady-state final value. The time interval for $i_c$ to rise from 10% to 90% of its final value $I_c$ is denoted as $t_r$ whereas the time interval between 0.1 $I_c$ to 0.1 $V_{ce}$ is called ton. Similarly, the experimental measurements for the turn-off transient can be seen in Fig 1(b). The time delay between the turn-off of $V_{ge}$ and the instant of increase in $V_{ce}$ defines $t_{d}(off)$. After this delay, $V_{ce}$ increases to a peak value and finally settles to a steady-state value. The fall-time $t_f$ of $i_c$ defines the interval from 90% to 10% of its final value, while $t_{off}$ defines the interval between 0.1 $V_{ce}$ and 0.1 $I_c$. The tailing current time interval is defined from 10% of $I_c$ to 1% of $I_c$.

![Figure 1. Measured IGBT characteristic curve](image)

(a) IGBT turn-on characteristic curve  
(b) IGBT turn-off characteristic curve

3. MMC modelling with IGBT switching characteristic curve embedded

3.1. MMC mathematic model

The MMC topology diagram is shown in Figure 2. SMn is the MMC sub-module; $U_{ra}$, $U_{rb}$, $U_{rc}$ 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. The mathematic model of MMC is:

\[ U_x - e_x = \frac{1}{2} L_0 \frac{d i_x}{d t} \]  
\[ L_0 \frac{d i_{cirx}}{d t} + u_{cirx} = 0 \]  
\[ e_x = \frac{u_{max} - u_{px}}{2} \]
\[ i_{\text{cirx}} = \frac{i_{px} - i_{nx}}{2} \]
\[ u_{\text{cirx}} = \frac{u_{px} + u_{nx} - u_{dc}}{2} \]

Where \( x = a, b, c; \) \( e_x \) is inside MMC virtual voltage; \( i_{\text{cirx}} \) is the inside MMC circle current; and \( u_{\text{cirx}} \) is the unbalanced voltage caused by \( i_{\text{cirx}}. \)

### 3.2. Work status analysis of half bridge MMC sub-module

The circuit of half bridge MMC sub-module is shown in Figure 3. When the MMC sub-module works normally, the output voltage \( u_{\text{sm}} \) is only determined by the input current \( i_{\text{sm}} \) and the module controlled PWM. Analysis the half bridge module work status can based on the IGBT and diode’s characteristic. Considering the switching dead-time effort, there are 3 kinds of controlled PWM exist when the half bridge sub-module works normally: \( T_1T_2=10, \) \( T_1T_2=00, \) \( T_1T_2=01. \) Furthermore, considering the direction of the input current (the current positive direction is shown as Figure 3), there are 6 kinds of work status need to be analyzed. Figure 4 shows all sub-module equivalent circuit at normal work statuses.

![Figure 2. MMC topology diagram](image)

![Figure 3. Half bridge MMC sub-module](image)

(a) Working state analysis when \( T_1T_2=10 \)
(b) Working state analysis when \( T_1T_2=10 \)
(c) Working state analysis when \( T_1T_2=01 \)

![Figure 4. MMC sub-module work equivalent circuit analysis](image)
Numbering every work equivalent circuit of half bridge MMC sub-module as shown in Figure 4, considering the switching dead time effort, the status switching between different working statuses can be several kinds, as shown in Figure 5.

![Figure 5. MMC sub-module working status switching analysis](image)

From the half bridge MMC sub-module work equivalent circuit, several conclusions can be got:

- Between status1 and status2, status5 and status6, the status switching doesn’t change the equivalent circuit, although the controlled PWM changes.
- Considering the current frequency is much smaller compared with the sample time (simulation sample time should be less than 1 μs), 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.
- Between status2 and status3, status4 and status5, status switching caused by the PWM signal is influenced by the IGBT switching characteristic.

Based on the above analysis of half 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 or not. If the controlled PWM at current sample time can be present as $T_1T_2 (k)$, and the controlled PWM at last sample time can be present as $T_1T_2 (k-1)$, defining the positive current direction as shown in Figure 3, defining the status switching sign as $F$, the $F$ can be get as follow:

$$F = \begin{cases} 
1 & T_1T_2(k) = 00, T_1T_2(k-1) = 01, i_{sm} > 0 \\
2 & T_1T_2(k) = 01, T_1T_2(k-1) = 00, i_{sm} > 0 \\
3 & T_1T_2(k) = 10, T_1T_2(k-1) = 00, i_{sm} < 0 \\
4 & T_1T_2(k) = 00, T_1T_2(k-1) = 10, i_{sm} < 0 \\
0 & \text{else} 
\end{cases}$$  \hspace{1cm} (6)

### 3.3. IGBT switching characteristic curve embedded half-bridge MMC modeling

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

When $F=1$ or $F=2$,

- $i_{c1} = 0$  \hspace{1cm} (7)
- $i_{d1} = i_{sm,s} = i_{sm} - i_{sm,x}$  \hspace{1cm} (8)
- $i_{sm,x} = i_{c2}$  \hspace{1cm} (9)
- $i_{d2} = 0$  \hspace{1cm} (10)
- $u_{sm} = V_{ce2}(i_{c2})$  \hspace{1cm} (11)

When $F=3$ or $F=4$,

- $i_{sm,s} = i_{c1}$  \hspace{1cm} (12)
- $i_{d1} = 0$  \hspace{1cm} (13)
- $i_{c2} = 0$  \hspace{1cm} (14)
- $i_{d2} = -i_{sm,x} = -(i_{sm} - i_{sm,s})$  \hspace{1cm} (15)
- $u_{sm} = u_c - V_{ce1}(i_{c1})$  \hspace{1cm} (16)

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

After half bridge sub-module calculation, using the equation (1) ~ (5), IGBT switching characteristic curve embedded half-bridge MMC model is built.
4. Real time simulation based on FPGA

Based on the proposed IGBT switching characteristic curve embedded half-bridge MMC model, do real time simulation using Xsim_FPGA board (an Xsim FPGA simulator based on Xilinx VC709). The real time simulation test hardware configuration is shown as Figure 6. Using RTDS as MMC controller, the controlled PWM is sent by optical fibre. And the simulation results are sent to Xsim simulator for data display and management. The FPGA code structure is shown as Figure 7.

![Real time simulation hardware configuration](image1)

**Figure 6.** Real time simulation hardware configuration

![FPGA realization code structure](image2)

**Figure 7.** FPGA realization code structure

The real time simulation sample time is 200ns. The simulation results are shown as Figure 8.

![Simulation results](image3)

**Figure 8.** Real time simulation results details about IGBT turn-on and turn-off
Figure 8(a) is the IGBT voltage figure at the time of IGBT turning off. From Figure 8(a), it can be seen that, the IGBT voltage turning off process exists for about 2us; the peak voltage is 1900V, and the steady voltage is 1700V after the IGBT turning off. Figure 8(b) is the IGBT voltage figure at the time of IGBT turning on. From Figure 8(a), it can be seen that, the IGBT voltage turning on process exists for about 1us. When the voltage falls to 0, there is an oscillation, and the oscillation process exists for about 4us. Figure 8(c) is the IGBT current figure at the time of IGBT turning on. From Figure 8(c), it can be seen that, the IGBT current turning on process exists for about 3us. The peak current is 1400A; the steady current is 700A after the IGBT turning on. Figure 8(d) is the IGBT current figure at the time of IGBT turning off. From Figure 8(c), it can be seen that, the IGBT current turning off process exists for about 1.5us. And the tail current is almost 0. From the real time simulation results, it can be seen that, the dynamic process is correct, and this can prove that the proposed IGBT switching characteristic curve embedded half-bridge MMC modeling method is correct.

5. Conclusion
In this paper, an IGBT switching characteristic curve embedded half-bridge MMC modelling method 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. Based on the proposed model, a FPGA real time simulation test is carried out; the simulation results prove that, the proposed model is correct.

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