Practical Analytical Model and Comprehensive Comparison of Power Loss Performance for Various MMCs based on IGCT in HVDC Application

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Abstract—This paper gives comprehensive analysis and characterization of power loss of high power integrated gate commutated thyristor (IGCT) in modular multilevel converter (MMC) for high-voltage dc (HVDC) application. The practical scheme, power loss models, calculation methods, characterization of MMC based on IGCT are analyzed in detail. Especially, comprehensive comparison of both half-bridge MMC (HB-MM) and full-bridge MMC (FB-MM) based on IGCT, press-pack IGBT, module-type IGBT, press-pack IEGT and module-type IEGT are analyzed in the paper. According to the study in the paper, the snubber power loss of MMC based on IGCT is far less than the conduction and switching power losses. Both the conduction and switching power losses of IGCT are always lower than that of press-pack and module-type IGBTs and IEGTs in MMC. The power loss of FB-MM is higher than that of HB-MM with the same transmission power because more switches are employed in FB-MM. If taking diodes into account, the HB-MM and FB-MM based on IGCT can decrease power loss about 1.9%~49.3% and 8.3%~45.1% under different operation states, respectively. The study in this paper will provide valuable reference and promote the application of IGCT in MMC.

Index Terms—Power loss, IGCT, IGBT, IEGT, modular multilevel converter, high voltage dc.

I. INTRODUCTION

HIGH voltage dc transmission technology based on voltage source converter (VSC-HVDC) can control active and reactive power independently and quickly, which enhances flexibility of power transmission greatly and becomes one of the most potential technology for power transmission [1]-[5]. Recently, VSC-HVDC technology is developing rapidly, a lot of VSC-HVDC systems have been built all over the world and more systems are building [6]-[8].

In VSC-HVDC system, the VSC is the most important core to achieve voltage conversion and power management. The solutions for VSC mainly contain two-level, three-level and modular multilevel converters [9]-[11]. Compared with two-level and three-level converters, modular multilevel converter (MMC) employs module-series technology and avoids switch-series, which reduces the technical threshold of VSC-HVDC greatly. Moreover, MMC has advantages in power quality, power loss, reliability, etc., therefore MMC has become the hottest VSC technology for HVDC application, and most of the practical VSC-HVDC systems are built based on MMC after the finding of MMC [12]-[14].

Because insulated gate bipolar transistor (IGBT) has a lot of advantages, such as simple driving circuit, low driving power, fast switching speed, it has been widely used in VSC-HVDC application [15]-[16]. Especially, until now, almost all the commissioned MMC projects are built based on IGBT. Although IGBT has some outstanding advantages, compared with current-mode devices, the on-state voltage drop of IGBT is still relatively high, and the current capability is still relatively low, so there is still plenty of room for improvement.

The applications of VSC-HVDC are now rapidly increasing, and the voltage and capacity of the VSC-HVDC system are becoming more demanding. In China, a dc transmission grid is under construction, and the voltage and capacity of the MMCs in which reaches ±500 kV/3000 MW. A ±800 kV/5000 MW MMC project is also under planning for long-distance bulk power transmission through overhead lines. In high-voltage and high-power MMC applications, there will be strong attraction and great application prospect for the switching devices with higher current capability.

Because the number of levels of MMC is usually very high, a very low switching frequency can be used. Therefore, conduction loss become prominent in the total loss of MMC, and on-state voltage drop of the switching devices become the chief factor of the efficiency. Half-bridge sub-module based MMCs (HB-MMcs) cannot block the dc-side short-circuit current, which limit its overhead line applications. Some improved MMC topologies, such as full-bridge sub-module based MMCs (FB-MMcs), have dc fault blocking capability by
employing additional switching devices in the submodule [17]. However, the arm current also flows through these additional switching devices and results in extra conduction losses. Switching devices with lower on-state voltage drop become very attractive for these applications.

Compared with IGBT, integrated gate commutated thyristor (IGCT) has lower on-state voltage drop, especially the voltage and current capacities are higher, which may improve the performances of IGBT in high-voltage and high-power applications [18]-[20]. In fact, a key drawback for IGCT is slow switching speed, which cannot be accepted by most of VSC applications. However, in high-voltage and high-power MMC applications, the multilevel solution can improve the ac harmonic greatly, so the switching frequency of switches can be reduced significantly [21]-[22], which weakens the drawback of IGCT and provides a good application opportunity.

However, until now, the application of IGCT in MMC is seldom discussed in literatures. Literatures [23]-[24] discusses potential of IGCT in HVDC application and the efficiency issue is also concerned, however the analyses are still not detailed and comprehensive, especially some key conclusions about power loss characterization of IGCT in MMC application are not achieved. Based on the situation mentioned above, this paper gives a comprehensive analysis and characterization of IGCT in MMC application. The study in this paper will provide valuable reference and promote the application of IGCT in MMC.

The paper is organized as follows. Section II introduces the MMC based IGCT and basic analytical models. Section III proposes power loss models for MMC based on IGCT, includes conduction loss, switching loo and snubber loss models. Section IV gives power loss calculation demonstrations. On this basis, Section V gives a comprehensive power loss characterization of MMC based on IGCT. Section VI compares the power loss performances of HB-MMCs based on IGCT, press-pack IGBT, module-type IGBT, press-pack IEGT and module-type IEGT. Section VII further compares the power loss performances for FB-MMCs.

II. MMC BASED ON IGCT

A. Topology of MMC based on IGCT

Fig. 1 gives topology of MMC based on IGCT. The typical snubber circuit of IGCT is composed by a resistor $R_{xis}$, an inductor $L_{xis}$, a diode $D_{xis}$ and a capacitor $C_{xis}$. The inductor $L_{xis}$ is employed to limit current rise rate when IGCT turn-on, the resistor $R_{xis}$ is employed to absorb energy which stores in $L_{xis}$ when IGCT turn-off. In addition, $R_{xis}$, $C_{xis}$ and $D_{xis}$ also compose a RCD snubber circuit to limit overvoltage when IGCT turn-off [25]. In Fig. 1, $x$ represents symbols $ap$, $an$, $bp$, $bn$, $cp$ or $cn$.

Besides the difference with MMC based on IGBT and IEGT, the issues about driving power source and retrigger should be designed carefully for MMC based on IGCT. In fact, the driving power source of sub-module in MMC based on IGCT should be shut down after the discharge of the dc capacitor of sub-module, or else the two IGCTs in submodule may turn on because of special mechanism of IGCT driving circuit, which will cause short-circuit fault. Thus the driving power source should have high reliability and the power-off and power-on logic should be designed carefully. Especially, because IGCT belongs current-controlled device, the driving power will be higher than that of IGBT and IEGT.

B. Basic Analytical Models of MMC

No matter IGCT-based, IGBT-based or IEGT-based, the operation of MMC is still similar, the basic operation waveforms of MMC are shown in Fig. 2. Each sub-module generates square wave with 50% duty ratio and there are different phase-shift between different sub-modules, so each arm will generate multilevel wave to imitate sine wave, we have,
TABLE I

<table>
<thead>
<tr>
<th>State</th>
<th>Bridge current</th>
<th>Switching function</th>
<th>Commutation behavior</th>
<th>Power loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>State 1</td>
<td>$i_{bep}&gt;0$</td>
<td>$S_i=1$</td>
<td>$D_i$</td>
<td>$v_{D_Di}$</td>
</tr>
<tr>
<td>State 2</td>
<td>$S_i=0$</td>
<td>$S_{b2}$</td>
<td>$v_{D_{S2}2}$</td>
<td></td>
</tr>
<tr>
<td>State 3</td>
<td>$i_{bep}&lt;0$</td>
<td>$S_i=1$</td>
<td>$S_{b3}$</td>
<td>$v_{D_{S3}2}$</td>
</tr>
<tr>
<td>State 4</td>
<td>$S_i=0$</td>
<td>$D_i$</td>
<td>$v_{D_{D2}2}$</td>
<td></td>
</tr>
</tbody>
</table>

State 1→State 2: $S_{i1}=1→0$ D_{D1} S_{i2} T E_{DecD1}, E_{SonS2} T
State 2→State 1: $S_{i1}=0→1$ D_{D1} S_{i2} T E_{SoffS2} T
State 3→State 4: $S_{i1}=1→0$ D_{D2} S_{i2} T E_{SoffS1}
State 4→State 3: $S_{i1}=0→1$ D_{D2} S_{i2} T E_{DecD2}, E_{SonS1}

\[ v_{ap} = \frac{V_d}{2} - v_u \]
\[ v_{an} = \frac{V_d}{2} + v_u \]

where $v_{ap}$ and $v_{an}$ are voltages of upper and lower arms in phase $a$, respectively, $v_u$ is equivalent output voltage of phase $a$, $V_d$ is dc voltage of MMC.

In steady state, all the dc voltages of sub-modules are equal and can be defined $V_C$, we have,

\[ v_u = nV_C \]

or

\[ v_u = M \frac{V_d}{2} \sin(wt) \]

where $M$ is modulation ratio, $w$ is angular frequency.

Then the MMC can be equivalent to two sine voltages $v_u$ and $v_{ua}$ connected with an inductor, the magnitude and direction of power flow can be adjusted by controlling the magnitude and direction of phase shift angle $\varphi$ between $v_u$ and $v_{ua}$. The output ac current can be derived as,

\[ i_a(t) - i_n(0) = \int_0^t v_u - v_{ua} \frac{dt}{L} \]

where $L$ is equivalent inductance which contains arm inductance, transformer inductance and ac grid inductance.

The arm currents can be derived as,

\[ i_{ap} = \frac{i_u + i_d}{2} \]
\[ i_{an} = \frac{-i_u + i_d}{2} \]

where $i_{ap}$ and $i_{an}$ are currents of upper and lower arms in phase $a$, respectively, $I_d$ is dc current of MMC.

III. POWER LOSS MODEL OF MMC BASED ON IGCT

A. Conduction Loss Model for IGCT-MMC

Conduction power loss is mainly related to the current which flows through switches and diodes. For different operation states, the current flows through components will be different. However, if the arm current $i_{a}$ (x represents ap, an, bp, bn, cp or cn) and switching states of sub-module are known, the current operation states will be known, as shown in Fig. 3. In Fig. 3, $S_{a1}$ represents switching function of the sub-module. When $S_{a1}$ is turned on and $S_{a2}$ is turned off, then $S_{a1}=1$; when $S_{a1}$ is turned off and $S_{a2}$ is turned on, then $S_{a2}=0$.

The commutation behaviors of sub-module in Fig. 3 can be summarized as Table I. When $i_a > 0$ and $S_{a1}=1$, the current flows through the diode $D_{a1}$; when $i_a > 0$ and $S_{a1}=0$, the current flows through the switch $S_{a2}$; when $i_a < 0$ and $S_{a1}=1$, the current flows through the switch $S_{a1}$; when $i_a < 0$ and $S_{a1}=0$, the current flows through the diode $D_{a2}$. Then, the current flows through the switches and diodes can be described as,

\[ \begin{align*}
\dot{i}_{S_{a1}} &= ABS[S_{a1}i_aSGN(-i_a)] \\
\dot{i}_{S_{a2}} &= ABS[(1-S_{a1})i_aSGN(i_a)] \\
\dot{i}_{D_{a1}} &= ABS[S_{a1}i_aSGN(i_a)] \\
\dot{i}_{D_{a2}} &= ABS[(1-S_{a1})i_aSGN(-i_a)]
\end{align*} \]

where $SGN(x)$ is sign function, $SGN(x)=1$ when $x>0$, or else $SGN(x)=0$; $ABS(x)$ is absolute value function to get the positive value of current, $i_{S_{a1}}, i_{S_{a2}}, i_{D_{a1}}$ and $i_{D_{a2}}$ are currents which flow through $S_{a1}, S_{a2}, D_{a1}$ and $D_{a2}$, respectively.

The transient conduction power loss can be derived based on the product of current and voltage drop of switches and diodes. The dataspheet of switches and diodes usually provide the relation curve between voltage drop and the conducting current. The typical mathematical method is to linearize the relation curve with two sections, then the voltage drop of switches and diodes in sub-module can be derived as,

\[ \begin{align*}
\dot{v}_{S_{a1}} &= v_{S_{a0}} + R_{S_{a1}} i_{S_{a1}} \\
\dot{v}_{S_{a2}} &= v_{S_{a0}} + R_{S_{a2}} i_{S_{a2}} \\
\dot{v}_{D_{a1}} &= v_{D_{a0}} + R_{D_{a1}} i_{D_{a1}} \\
\dot{v}_{D_{a2}} &= v_{D_{a0}} + R_{D_{a2}} i_{D_{a2}}
\end{align*} \]

where $v_{S_{a1}}, v_{S_{a2}}, v_{D_{a1}}$ and $v_{D_{a2}}$ are voltage drops of $S_{a1}, S_{a2}, D_{a1}$ and $D_{a2}$, respectively, $V_{S0}$ and $V_{D0}$ are threshold voltage of switch and diode, respectively, $R_S$ and $R_D$ are slope resistance.

Then, the conduction power loss of a sub-module in MMC can be derived as,

\[ P_{cond} = \frac{1}{T} \int_0^T (v_{S_{a1}}i_{S_{a1}} + v_{S_{a2}}i_{S_{a2}} + v_{D_{a1}}i_{D_{a1}} + v_{D_{a2}}i_{D_{a2}}) dt \]

where $T$ is line frequency.

Therefore, the conduction power loss of a whole MMC can be achieved by adding the conduction power losses of all the sub-modules.

B. Switching Loss Model for IGCT-MMC

Because the turn on and turn off processes of switches and diodes are not ideal, the voltage is increasing (or decreasing) while the current is decreasing (or increasing) in the switching process, then the switching power loss is caused and it can be calculated by multiplying the voltage and current in the switching process. For different operation states of MMC, the switching behaviors of switches and diodes are different, as show in Fig. 3.

When $i_a > 0$ and $S_{a1} = 1→0$, the diode $D_{a1}$ turns off, the switch $S_{a2}$ turns on, the switching power losses contain: turn off loss of $D_{a1}$ and turn on loss of $S_{a2}$. When $i_a < 0$ and $S_{a1} = 0→1$, the diode $D_{a1}$ turns on, the switch $S_{a2}$ turns off, because the turn on loss of diode is very small and it is usually can be ignored, so the
ELATED WITH DEVICE CURRENT, VOLTAGE

\[
E_{\text{L}} = E_{\text{Soff}} + E_{\text{Drec}} + E_{\text{Son}}
\]

This equation shows the total energy loss in a sub-module of MMC.

**Snubber Loss Model for IGCT-MMC**

Compared with MMC based on IGBT and IEGT, there is \( \text{d}i/\text{dt} \) snubber circuit in MMC based on IGCT, so additional snubber power loss should be considered. From Fig. 3, when \( i_x < 0 \) and \( S_{xi} \) is switched from 0 to 1, the inductor \( L_{asi} \) will store energy; when \( S_{ai} \) is switched from 1 to 0, the energy in inductor \( L_{asi} \) will release energy. Fig. 4 gives possible paths for inductor \( L_{asi} \) to release energy. From Fig. 4, the stored energy not only dissipate in RCD snubber circuit, but also provide turn off loss of IGCT, moreover a small part energy flows to dc capacitor \( C_{xi} \). However, according to the analysis in [26], 80%–90% stored energy of \( L_{asi} \) in turn on process will dissipate in snubber circuit.

Similarly, the situation is the same when \( i_x > 0 \). Therefore, the snubber energy loss of a sub-module of MMC based on IGCT in a switching period can be calculated approximately,

\[
E_{\text{Snubber}} = \frac{1}{2} L_{asi} I_{\text{Snubber}}^2
\]

where \( I_{\text{Snubber}} \) is arm current when \( S_{ai} \) is switched between 0 and 1.

Then the switching power loss of snubber in a sub-module can be achieved by adding all the snubber energy in 1 s. Therefore, the switching power loss of a whole MMC can be achieved by adding the switching power losses of all the sub-modules.

### IV. POWER LOSS SIMULATION CALCULATION OF MMC BASED ON IGCT

According to the analysis in Section III, the power losses of MMC based on IGCT are related with device current, voltage and switching behaviors, it is very complicated to calculate. In this paper, the power loss model of IGCT and the commutation characteristics of MMC are combined, the power loss of MMC can be get by the employ of Matlab. The calculation method in this paper is simple and effective, which can be used to different MMC topologies easily.
Fig. 5. Calculation demonstration of conduction power loss for MMC based on IGCT.

A. Conduction Loss for IGCT-MMC

Fig. 5 gives a calculation demonstration of conduction power loss for MMC based on IGCT. Firstly, according to the analysis in Section II, the arm current and switching signals can be obtained based on the specified operation state and modulation method. Then, from (6) and (7), the conducting current and voltage drop of all the switches and diodes can be obtained. The transient power loss can be achieved by multiplying current and voltage, then the conduction loss energy during one operation period can be obtained based on the integral of transient power loss, that is shaded area in Fig. 5. Then the conduction power loss of a sub-module can be obtained by adding the conduction loss energy during 1s. In Fig. 5, the parameters of MMC are the same with Section V, and the MMC operates in rectifier state with -600 MW transmission power.

B. Switching Loss for IGCT-MMC

Fig. 6 gives a calculation demonstration of switching power loss for MMC based on IGCT. Firstly, according to the analysis in Section II, the arm current and switching signals can be obtained based on the specified operation state and modulation method. From Section IV.A, the switching behaviors and related energy losses can be derived based on the switching states and current polarity at switching time. Then accumulating the energy losses at every switching time one by one, the switching losses of all the switches and diodes can be obtained. Therefore, the switching losses of a sub-module can be obtained by adding the switching losses of all the switches and diodes during 1s.

V. POWER LOSS CHARACTERIZATION OF MMC BASED ON IGCT

A. Analytical Parameters Based on Practical HVDC Project

In order to analyze power loss characterization of MMC based on IGCT, the Nanao project (the first multi-terminal VSC-HVDC system in the world) is taken as a target. The IGCT is 5SHY 35L4521 produced by ABB. The design parameters are shown in Table II.

B. Power Loss Distribution for IGCT-MMC

Based on the analysis above, Fig. 8 gives different components of power loss for MMC based on IGCT under rectifier, inverter and reactive power states.
Fig. 8. Different components of power loss for MMC based on IGCT. (a) Conduction power loss. (b) Switching power loss. (c) Snubber power loss.

Fig. 9. Power loss of MMC based on IGCT with different switching frequency. (a) Rectifier state. (b) Inverter state. (c) Reactive power state.

<table>
<thead>
<tr>
<th>Table II</th>
<th>Parameters of MMC based on IGCT for Power Loss Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Unit</td>
</tr>
<tr>
<td>Power</td>
<td>MVA</td>
</tr>
<tr>
<td>AC grid voltage</td>
<td>kV</td>
</tr>
<tr>
<td>AC terminal voltage of MMC</td>
<td>kV</td>
</tr>
<tr>
<td>DC terminal voltage of MMC</td>
<td>kV</td>
</tr>
<tr>
<td>Turn ratio of transformer</td>
<td>1</td>
</tr>
<tr>
<td>DC voltage of sub-module</td>
<td>V</td>
</tr>
<tr>
<td>Number of sub-module</td>
<td>1</td>
</tr>
<tr>
<td>DC capacitance of sub-module</td>
<td>μF</td>
</tr>
<tr>
<td>Inductance of AC grid</td>
<td>mH</td>
</tr>
<tr>
<td>Inductance of transformer</td>
<td>mH</td>
</tr>
<tr>
<td>Inductance of MMC arm</td>
<td>mH</td>
</tr>
<tr>
<td>Capacitance of snubber</td>
<td>μF</td>
</tr>
<tr>
<td>Inductance of snubber</td>
<td>μH</td>
</tr>
<tr>
<td>Resistance of snubber</td>
<td>Ω</td>
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<tr>
<td>IGCT model</td>
<td>-</td>
</tr>
<tr>
<td>Diode model</td>
<td>-</td>
</tr>
</tbody>
</table>

For conduction power loss, the power is transferred from ac side to dc side under rectifier state, the arm current $i_a$ has negative bias, the current flows through upper switch and lower diode during most of the time. From Fig. 5, $S_a=0$ for most of the time when $i_a<0$, so the current flows through $D_{a2}$ during most of the time, and the conduction power loss of $D_{a2}$ is the highest. Similarly, in inverter state, the power is transferred from dc side to ac side, the arm current $i_a$ has positive bias, the current flows through $S_{a2}$ and $D_{a1}$ during most of the time. $S_a=0$ for most of the time when $i_a>0$, so the current flows through $S_{a2}$ during most of the time, and the conduction power loss of $S_{a2}$ is the most. In reactive power, the active power is zero, the arm current $i_a$ has no bias, the current flows through $S_{a2}/D_{a1}$ and $S_{a1}/D_{a2}$ with similar time, so the conduction power losses of components are similar.

For conduction power loss, because the transmission power under rectifier and inverter states are the same, just the direction of power flow is opposite, so the switching power losses of upper switch under rectifier and inverter states are basically the same with that of lower switch under inverter and rectifier states, respectively. In reactive power state, the upper and lower switches have the same switching power losses. The same features are also for upper and lower diodes.

For snubber power loss, it has a little difference under different operation states with the same power. The snubber power loss in rectifier state is higher than that in inverter and reactive power states, and the reactive power state has the lowest snubber power loss. However, no matter any operation state, the snubber power loss of MMC based on IGCT is far less than the conduction and switching power losses.

C. Power Loss of IGCT-MMC with Different Frequency

Fig. 9 gives power loss of MMC based on IGCT with different switching frequency. It can be seen that the switching power losses of IGCT and diode and the snubber power loss increase with the increase of switching frequency under rectifier, inverter and reactive power states. The power loss under reactive power state is lower than that under active power state,
the rectifier state has the highest power loss. With the low switching frequency, the conduction power loss is higher than the switching power loss. However, as the increase of the switching frequency, the switching power loss will become higher. The snubber power loss is always far less than the conduction and switching power losses.

D. Power Loss of IGCT-MMC with Different Power

Fig. 10 gives power loss of MMC based on IGCT with different power. It can be seen that the power losses of IGCT and diode and the snubber power loss increase with the increase of power under rectifier, inverter and reactive power states. Under rectifier state, the power is transferred from ac side to dc side, so the negative part of bridge-arm currents is more than positive part, the current flows as Fig. 3(b) in most of time, then the switch S1 and the diode D2 take most of the loss. Under inverter state, the power is transferred from dc side to ac side, so the positive part of bridge-arm currents is more than negative part, the current flows as Fig. 3(a) in most of time, then the switch S2 and the diode D1 take most of the loss. Under reactive power state, there is no power transmission in dc side, so the positive part of bridge-arm currents is almost the same with negative part, and then the upper and lower devices almost take the same power losses.

In Fig. 8~10, the transmission powers are -600 MW, 600 MW and 600 MVar for rectifier, inverter and reactive power states, respectively. The power losses of S1, D1, S2 and D2 are the sum of all the components in the same position (upper IGCT, upper diode, lower IGCT and lower diode) of sub-modules.

VI. POWER LOSS COMPARISON OF MMCs BASED ON IGCT, IGBTs AND IEGTs

Nowadays, almost all the MMCs in the world are built based on IGBT, few MMCs are built based on IEGT, this paper will give a comprehensive comparison about power loss for MMCs based on IGCT, IGBT and IEGT.

A. IGCT, IGBT and IEGT for Comparison

For MMCs based on IGCT, IGBT and IEGT with the same voltage, the characteristic operation currents and voltages are almost the same, the power loss is different because the performance of IGCT, IGBT and IEGT are different and the snubber circuit is added for MMC based on IGCT. In order to compare the power loss of MMCs based on IGCT, IGBT and IEGT for HV MW applications, the 4.5kV IGCT, press-pack IGBT, module-type IGBT, press-pack IEGT and module-type IEGT produced by ABB and TOSHIBA are employed, and all the devices are commercial products, as shown in Fig. III. In fact, the definition of current rating for IGCT in practice is different with IGBT and IEGT, the max turn-off current is current rating for IGCT and the dc collector current is current rating for IGBT or IEGT. In this paper, the 4500V/4000A IGCT
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switching power loss is higher. In fact, from Table III, although the turn-off energy of IGCT is higher than that of IGBTs and IEGTs with the same voltage and current conditions, the turn-on energy of IGCT is far lower than that of IGBTs, therefore the switching power loss of IGCT is possible to be lower.

Similar with the operation of MMC in Section V, the transmission powers are -600 MW, 600 MW and 600 Mvar for rectifier, inverter and reactive power states in Fig. 11-13. Table IV summarize the power loss results of MMC based on IGCT, IGBTs and IEGTs during rated operation. Under rectifier state, compared with the MMC based on IGCT, the MMC based on press-pack IGBT, module-type IGBT, press-pack IEGT and module-type IEGT increase loss for 1.9%, 26.9%, 31.2% and 16.6%, respectively. Under rectifier state, the MMC based on press-pack IGBT, module-type IGBT, press-pack IEGT and module-type IEGT increase loss for 28.8%, 42.4%, 49.3% and 34.8%, respectively. Under reactive power state, the MMC based on press-pack IGBT, module-type IGBT, press-pack IEGT and module-type IEGT increase loss for 12.7%, 30.3%, 38.0% and 21.7% respectively.

C. Comparison of Power Loss with Different Switching Frequency

Fig. 13 gives power loss of MMC with different switching frequency. It can be seen that, no matter IGCT, IGBTs and IEGTs based, the power loss of MMC increases with the increase of switching frequency. The MMC based on module-type IGBT and press-pack IEGT have the highest power loss during all the range. The MMC based on IGCT always has the lowest power loss under inverter and reactive power states. Under rectifier state, the MMC based on press-pack IGBT has the lowest power loss when the frequency is low. However, this is because the power loss of diodes integrated in press-pack IGBT is lower during this area, the power loss caused by IGCT is still lower than that caused by press-pack IGBT.

D. Comparison of Power Loss with Different Power

Fig. 14 gives power loss of MMC with different power. It can be seen that, the MMC based on IGCT always has the lowest power loss during rectifier, inverter and reactive power states, and the MMC based on press-pack IEGT has highest power loss. In Fig. 14, because the limitation of modulation ratio of MMC, the maximum reactive power which can generate to power grid for MMC is just about 200 MVar.
The MMC based on full switches, both the conduction and switching power losses of IGCT are always lower than that of module IGBTs and IEGTs. This find is better than that of module IEGT increase loss for half bridge sub-module (HB-MMC). Because the conduction performance of press-pack IEGT is the same with HB-MMC based on IGCT, the conduction power loss changes to be greater for HB-MMC. However, the conduction power loss changes to be greater for FB-MMC. The FB-MMC based on IGCT has the lowest power loss, however, the power loss for FB-MMC based on module-type IGBT changes to be the highest.

In fact, as shown in Fig. 16, compared with HB-MMC, the conduction power loss changes to be greater for FB-MMC. Because the conduction performance of press-pack IEGT is better than that of module-type IGBT, so the FB-MMC based on module-type IGBT has the highest power loss. No matter any case, if we just consider switches, both the conduction and switching power losses of IGCT are always lower than that of IGBTs and IEGTs. This find is the same with HB-MMC.

Table V summarizes the power loss results of FB-MMC based on IGCT, IGBTs and IEGTs during rated operation. Under rectifier state, compared with the FB-MMC based on IGCT, the FB-MMC based on press-pack IGBT, module-type IGBT, press-pack IEGT and module-type IEGT increase loss for 10.1%, 42.3%, 33.3% and 28.6%, respectively. Under inverter state, the FB-MMC based on press-pack IGBT, module-type IGBT, press-pack IEGT and module-type IEGT increase loss for 12.5%, 45.1%, 34.7% and 29.8%, respectively. Under reactive power state with $Q = -600$ MVar, the FB-MMC based on press-pack IGBT, module-type IGBT, press-pack IEGT and devices in the sub-module. This section will give power loss comparison about FB-MMC.

A. Comparison of Power Loss Distribution

Fig. 15 shows power losses distribution for different components in FB-MMCs based on IGCT, IGBTs and IEGTs. Similar with the analysis in Section VI, the upper switches and the lower diodes take most of the loss under rectifier state, the lower switches and the upper diodes take most of the loss under inverter state, and the power loss difference is not significant under reactive power states. The FB-MMC based on IGCT still has the lowest power loss, however, the power loss for FB-MMC based on module-type IGBT changes to be the highest.

In the analysis above, the MMC is mainly based on half-bridge sub-module (HB-MMC). However, HB-MMC cannot block the dc-side short-circuit current, which limit its overhead line applications. The MMC based on full-bridge sub-module (FB-MMC) is currently a popular scheme to block dc-side short-circuit fault by employing additional switching

VII. POWER LOSS COMPARISON OF FB-MMCs BASED ON IGCT, IGBTs AND IEGTS

In the analysis above, the MMC is mainly based on half-bridge sub-module (HB-MMC). However, HB-MMC cannot block the dc-side short-circuit current, which limit its overhead line applications. The MMC based on full-bridge sub-module (FB-MMC) is currently a popular scheme to block dc-side short-circuit fault by employing additional switching

![Image](https://example.com/image1.png)

Fig. 15. Power loss comparison with different components for FB-MMCs based on IGCT, IGBTs and IEGTs. (a) Rectifier state. (b) Inverter state. (c) Absorb reactive power state. (d) Generate reactive power state.

![Image](https://example.com/image2.png)

Fig. 16. Power loss comparison with different types for FB-MMCs based on IGCT, IGBTs and IEGTs. (a) Rectifier state. (b) Inverter state. (c) Absorb reactive power state. (d) Generate reactive power state.

### TABLE V

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<th>Type</th>
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<th>$P_{con}/$kW</th>
<th>$P_{sw}/$kW</th>
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module-type IEGT increase loss for 8.3%, 38.8%, 30.7% and 24.5% respectively. Under reactive power state with $Q = 600$ MVar, the FB-MMC based on press-pack IGBT, module-type IGBT, press-pack IEGT and module-type IEGT increase loss for 13.6%, 42.0%, 39.3% and 29.4% respectively.

It should notice that, different with HB-MMC, there are four-switches in FB sub-module. However, two couples are symmetrical, so we still use upper and lower switches to describe, when upper switches turn on, the output voltage of FB is positive and when lower switches turn on, the output voltage is negative or zero. In addition, because the modulation ratio of FB-MMC can be higher than 1, so the reactive power which can generate to power grid for FB-MMC can reach to 600 MVar.

**B. Comparison of Power Loss with Different Switching Frequency**

Fig. 17 gives power loss of FB-MMC with different switching frequency. It can be seen that, the power loss of FB-MMC still increases with the increase of switching frequency. The FB-MMC based on module-type IGBT and press-pack IEGT still have the highest power loss during all the range. However, the range changes to be wider for module-type IGBT than that in HB-MMC. The MMC based on IGCT always has the lowest power loss under all the operation states.

**C. Comparison of Power Loss with Different Power**

Fig. 18 gives power loss of FB-MMC with different power. It can be seen that, the power loss of FB-MMC is higher than that of HB-MMC with the same transmission power. The FB-MMC based on IGCT still has the lowest power loss during all the operation states, and the FB-MMC based on module-type IGBT and press-pack IEGT have the highest power loss.

**VIII. Conclusion**

The power loss performance of MMC based on IGCT for HVDC application is analyzed comprehensively in this paper. Especially, the comparison of MMCs based on IGCT, IGBTs and IEGTs is discussed in detail. According to the study in the paper, the snubber power loss of MMC based on IGCT is far less than the conduction and switching power losses. If we just consider switches, compared with MMC based on IGBTs and IEGTs, both the upper and lower IGCTs have the lowest power losses during all the operation states of MMC. Moreover, because the turn-on energy of IGCT is far lower than that of IGBTs and IEGTs, both the conduction and switching power losses of IGCT are lower than that of IGBTs and IEGTs. The power loss reduction of FB-MMC based on IGCT is more significant than that of HB-MMC based on IGCT because more switches are employed in FB-MMC. If taking diodes into account, the HB-MMC and FB-MMC based on IGCT can decrease power loss about 1.9%~49.3% and 8.3%~45.1% under...
different operation states, respectively. The study in this paper will provide valuable reference and promote the application of IGCT in MMC.

REFERENCES


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