Comparison of High Power IGBT, IGCT and ETO for Pulse Applications

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Abstract: This paper focuses on the comparison of the state-of-the-art high power devices. A behavioral power loss model is developed to conduct electro-thermal simulation of these devices. The junction temperature is observed through simulation. The high power devices are compared for pulse application based on losses and thermal handling capability. Moreover, device operation condition (current, voltage and frequency) can be optimized to maximize the utilization of the power switch.

I. INTRODUCTION

The Gate Turn-Off (GTO) thyristor is widely used in high voltage, high current utility applications. The state-of-the-art GTO device capacity has reached 6000V, 6000A [1]. However the GTO is hindered by its large storage time thus low switching frequency. Moreover it requires 1/3 or 1/5 of anode current to turn the device off. In industrial applications, the Insulated Gate Bipolar Transistor (IGBT) is favorable. The IGBT is a voltage controlled device, hence it requires less gate drive power, thus simplifies the gate driver design. Due to the non-latched transistor operation, the IGBT has shorter storage time, therefore pushes the IGBT to higher switching frequency. However, the large conduction voltage drop limits the popularity of IGBT at high voltage. Today, only 600A device is available at 6.5kV [2]. On the other hand, improved GTO devices emerge. Hard-driven and MOS-assisted technologies are used in the Integrated Gate Commutated Thyristor (IGCT) [3,4] and Emitter Turn-Off (ETO) thyristor [5-7]. These two devices use unity gain turn-off technique [8,9] to cut the storage time of GTO by ten times, thus increase the switching performance close to that of the IGBT. The low conduction loss and rugged structure make IGCT and ETO more favorable than IGBT. The latest IGCT and ETO devices have reached the same power level of GTO (i.e. 6000V, 6000A).

This paper studied high power IGBT, IGCT and ETO devices in pulse power applications. Detailed comparison is given in Section II. A behavioral power loss model is described in Section III. In Section IV, the loss model is used in conjunction with the thermal characteristics of the devices to evaluate these three devices in the pulse application. Finally, a conclusion is drawn in Section V.

II. HIGH VOLTAGE IGBT, IGCT AND ETO

2.1 IGBT Module

The current and voltage ratings of IGBT have increased significantly in the past decade. Today, 1200V, 1700V, 2500V and 3300V IGBTs are commercially available. Fig. 1 shows the 600A, 6500V Eupec IGBT module (FZ600R65KF1), which is currently the only available module at this voltage level.

![Fig.1 Physical arrange of 6.5kV IGBT module](image)

The 6.5kV IGBT is a reliable device designed for medium voltage applications [10]. The recommended bus voltage is 3kV. Using 3-level NPC topology, this device can be directly applied to 4.16kV AC industrial applications. The rated DC current for this device is 600A. Detailed evaluation on the device focuses on the on-state performance and switching performance.

2.2 IGCT

Substantial changes have been made to the traditional GTO devices to obtain the IGCT. The transparent layer design [11] of GTO lowers the on-state loss significantly. Novel gate ring design is employed to reduce the gate stray inductance. Unity gain turn-off is achieved in the IGCT. Fig.2 shows the investigated 4000A, 4500V ABB IGCT device (5SHY35L4503). Fig.3 shows the snubberless turn-off waveform of the IGCT obtained by the authors.
2.3 ETO

The ETO is a GTO-MOSFET hybrid device as shown in Fig.4 [12]. The operation mechanism of the ETO can be interpreted from the turn-on process and the turn-off process. During the ETO’s turn-on, the emitter switch Q_E is turned on and the gate switch Q_G is turned off and at the same time a high current pulse is injected in the GTO’s gate. During the ETO’s turn-off, the emitter switch Q_E is turned off and the gate switch Q_G is turned on, the GTO cathode current will be diverted to its gate almost instantly, realizing so-called “unity gain” turn-off. Fig. 5 shows the 4000A, 4500V ETO prototype developed by the authors. The snubberless turn-off ability of the ETO device is demonstrated in Fig. 6.

Table 1 summarizes the major electrical parameter of these three devices. It is shown that the IGBT has the highest conduction loss and switching losses among three types of devices. Further comparison will be given based on electrothermal simulation.

<table>
<thead>
<tr>
<th></th>
<th>IGBT (FZ600R65K1F)</th>
<th>IGCT (5SHY35L,4503)</th>
<th>ETO (ETO4045TA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-state Voltage (V)</td>
<td>5.84 (125°C, 750A)</td>
<td>1.788 (125°C, 1500A)</td>
<td>1.921 (125°C, 1500A)</td>
</tr>
<tr>
<td>Turn-on Loss (J)</td>
<td>9.0 (125°C, 3.6kV, 800A)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Turn-off Loss (J)</td>
<td>4.0 (125°C, 3.6kV, 800A)</td>
<td>4.2 (125°C, 2.2kV, 800A)</td>
<td>4.8 (125°C, 2kV, 800A)</td>
</tr>
</tbody>
</table>

* di/dt snubber eliminates the turn-on loss of IGCT and ETO

III. Behavioral Device Loss Model

The motivation to develop a behavioral loss model is to conduct fast circuit level simulation of these devices and predict their maximum junction temperatures (Tjmax). For this reason, it is not necessary to obtain accurate device waveform but requires accurate instantaneous power loss prediction. An accurate thermal impedance model is also needed. The calculated junction temperature will also update the power loss instantaneously based on the temperature
dependence of the power loss. This behavioral model is therefore very useful in topology optimization and device evaluation.

The following equations are used to calculate the device power losses.

\[ V_{\text{th}} = V_{\text{th0}} + k_v T \]

Equivalent on-state resistance:

\[ r_T = r_{T0} + k_{rT} T \]

Turn-on loss:

\[ E_{\text{on}} = E_{\text{on0}} + k_{\text{eon}} I \]

Turn-off loss:

\[ E_{\text{off}} = E_{\text{off0}} + k_{\text{off}} I \]

Diode reverse recovery loss (IGBT):

\[ E_{\text{rr}} = E_{\text{rr0}} + k_{\text{err}} I + k_{\text{err}2} I^2 \]

The junction-to-case thermal impedance is modeled as a three order thermal network.

\[ Z_{\text{thjc}}(t) = r_j (1 - e^{-t/\tau_{Cj}}) + r_c (1 - e^{-t/\tau_{Cj}}) + r_j (1 - e^{-t/\tau_{Cj}}) \]

The model parameters listed in above equations are extracted from experiments or manufacturer’s datasheets. The model is implemented in SABER for fast circuit simulation. Ideal switch is used to generate the voltage and current waveform then the behavioral loss model is invoked to calculate instantaneous power loss and instantaneous junction temperature.

To demonstrate the developed loss models, a 6000V Neutral Point Clamped (NPC) topology is evaluated (Fig. 7).

![Fig.7 NPC topology for evaluation](image)

It is clearly shown in the simulation results (Fig. 8), that the junction temperature can be directly predicted from the electro-thermal simulation. This technique is critical to our evaluation of these IGBT, IGCT and ETO in a pulse application.

IV. COMPARISON IN PULSE APPLICATION

The objective of our study is to compare these devices in a two seconds pulsed PWM operation. The load can be modeled as a variable frequency, unity power factor load. The frequency swings from 0 to 200Hz during 2 seconds operation. DC link voltage is 6000V utilizing 3-level Neutral Point Clamped (NPC) topology.

Each device is simulated at different load and switching frequency conditions. The junction temperature is predicted from the simulation and plotted in Fig. 9, 10 and 11. Comparison is also obtained at the same switching frequency for IGBT, IGCT and ETO but at different load conditions (Fig. 12).
Fig. 9 IGBT maximum junction temperature vs current and frequency

Fig. 10 IGCT maximum junction temperature vs current and frequency

Fig. 11 ETO maximum junction temperature vs current and frequency
A comparison criteria is developed by assuming a fixed maximum junction temperature for all three devices. The comparison results show that the IGBT has poor performance at the desired current level. On the other hand, the IGCT and ETO have approximately the same performance.

V. CONCLUSION

The state-of-the-art high power devices are studied in this paper. A behavioral loss model is developed and implemented in SABER to evaluate these devices. This methodology is used in a pulse application design. The comparison basis is power losses and thermal handling capability of the devices. The result data show that the IGCT and the ETO have better performance than the IGBT device in the intended application.

ACKNOWLEDGEMENT

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Reference:

[10] Thomas Schuetze, Herman Berg, Oliver Schilling, *The new 6.5kV IGBT module:a reliable device for medium voltage applications*