Prediction and Simulation Analysis of Current Turn-off Behavior of Low-Voltage DC Circuit Breaker

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Abstract. As the key breaker of hybrid DC circuit breaker, IGBT is the research focus of hybrid DC circuit breaker. In this paper, a steady state simulation model of IGBT is built based on the Darlongton equivalent structure. Through the actual output characteristics of IGBT, the feasibility of the steady-state simulation model of IGBT is verified. Then, a driving simulation model considering the positive and negative bias of IGBT drive output is built. In order to establish a more accurate transient model of IGBT, a semi-empirical MOS3 model considering weak inverse conductivity is adopted in the MOSFET model and a Gummel-Poon model considering multiple secondary effects is adopted in the BJT model. According to the experimental data, the feasibility of IGBT transient model is verified, and the construction of IGBT transient model under the DC breaking condition is completed.

1. Introduction

DC circuit breakers generally have three categories of topology: mechanical DC circuit breakers, solid-state DC circuit breakers and mechanical switches and solid-state switch combined with hybrid DC circuit breakers, compared to the first two kinds of circuit breakers, hybrid DC circuit breakers have the advantages of small on-state loss, fast breaking speed and so on[1]. Among them, the hybrid DC circuit breaker based on high power IGBT and its components is the future development direction of circuit breaker[2].

IGBT and its components are the main turn-off devices in hybrid DC circuit breakers. The transient electrical characteristics of IGBT have an important effect on the performance of hybrid DC circuit breakers[3][4]. Therefore, it is of great significance for the development of hybrid DC circuit breakers to build a simulation model of IGBT device in the low voltage DC opening condition and explore the influence factors of IGBT and its components on the current shutting performance of hybrid DC circuit breakers.

Therefore, in order to solve the above problems, this paper built a steady-state simulation model of IGBT based on the physical structure and working principle of IGBT device, and built a transient simulation model of IGBT based on the experimental data obtained from the double-pulse experimental
platform and the sensitivity analysis of model parameters. Last for 10 kv dc open circuit condition using IGBT transient model structures, the simulation model of IGBT turn-off current, the IGBT device for dc open circuit condition of transient electric property, and study the IGBT turn-off process under different influencing factors of electric current fault features, the topology of the hybrid dc circuit breaker design and open circuit characteristic research to provide guidance and basis.

2. IGBT Transient Model

2.1. Model Description
Fig.1 a) shows a cross section of a unit in an enhanced MOS, Fig.1 b) shows the structure of a bipolar transistor, and Fig.1 c) shows a cross section of an IGBT unit. The comparison of the three structure diagrams shows that IGBT has a P+ injection layer more than MOSFET. The layer structure, buffer N+ layer, drift N- layer and body P layer constitute a PNP-type bipolar structure[5]. Therefore, IGBT can be considered as a power device composed of MOSFET and bipolar transistor.

![IGBT structure diagram]

Fig.1 Physical structure diagram of different power devices

2.2. Static and Transient Model
The steady-state characteristic of IGBT, also known as output characteristic, is the relationship between collector current and collector voltage drop under different gate voltages of IGBT[6]. Except for the non-linear at $U_{GE(th)}$, the rest of it tends to be linear. IGBT is a Darlongton structure device that combines the flow characteristics of bipolar PNP transistor and the voltage control characteristics of N-channel MOSFET. Therefore, this structure is used to build circuit structure in the software.

At the same time, in order to obtain the output characteristics of IGBT simulation model, the steady-state test circuit diagram as shown in Fig.2 a) was designed based on the Darlongton structure and built in PSPICE. The simulation circuit is shown in Fig.2 b).

![IGBT steady-state model simulation circuit diagram]

Fig.2 IGBT steady-state model topology

In the transient process of IGBT devices, nonlinear parasitic capacitance plays a very important role in the electrical characteristics of the devices and the stability of DC circuit breakers. In the nonlinear
capacitance model, its characteristics can be specifically interpreted as "varistor-sensitive characteristics", that is, the characteristics of capacitance changing with voltage. Its relation curve is obtained from the data curves of input capacitance $C_{ies}$, output capacitance $C_{oes}$ and feedback capacitance $C_{res}$ in the device specification, as shown in Fig.3 b). They have the following conversion relationship with the inter-electrode capacitance of IGBT devices:

$$C_{ge} = C_{ies} - C_{res}$$
$$C_{ce} = C_{oes} - C_{ies} + C_{res}$$
$$C_{gc} = C_{res}$$

Matlab was used to get the mathematical model, and then the conversion relationship was combined to get the characteristics of inter-electrode capacitance, as shown in Fig.3 b). A nonlinear capacitance model suitable for IGBT transient model analysis was built by using the GValue element of ABM library in PSpice software.

$$C_{gf}$$

$$C_{Cef}$$

$$C_{oe}$$

$$C_{res}$$

$$C_{g}$$

$$C_{ao}$$

$$V_{ce}$$

$$V_{g}$$

$$V_{max}$$

$$X_j$$

$$X_{jl}$$

$$T_{ox}$$

$$\eta$$

$$V_{max}$$

a) Capacitance curve in IGBT datasheet  
b) IGBT inter-electrode parasitic capacitance curve

Fig.3 Two types of capacitance curves of IGBT devices

3. Parametric Sensitivity Analysis

There are two elements that have influence on the key index of IGBT transient model, namely N-type MOSFET and PNP type BJT. Since the software simulation parameters used in the steady-state model of the two components can no longer represent the transient characteristics of IGBT, it is necessary to extend the parameters of the component model. The mechanism model used in PSPICE for the two components in the transient model of IGBT is introduced in the following

3.1. MOSFET

There are three MOSFET models in PSPICE software, and the steady-state model of IGBT adopts MOS1 model, but it cannot meet the simulation requirements of IGBT transient model, so it is necessary to choose between MOS2 model and MOS3 model, both of which consider the actual electrical effects of many MOSFET devices. However, MOS2 model needs to set more physical parameters to modify the parameters in MOS2 model, while MOS2 model adopts the way of empirical formula to obtain parameters, which is more suitable for circuit simulation. Therefore, MOS2 model is adopted in the establishment of IGBT transient model.

From the establishment process of MOS3 model, it can be seen that in the establishment process of IGBT transient model, MOSFET element using MOS3 model needs to set five parameters, including $\eta$, $T_{or}$, $X_j$, $X_{jl}$, $V_{max}$.

There are two mechanism models of BJT element, namely Ebers-Moll model and Gummel-Pool model. At this time, only the Ebers-Moll model could not meet the IGBT transient model simulation requirements, so the Gummel-Pool model considering the second-order effect was needed. Fig.4 shows the equivalent schematic diagram of the Gummel-Pool model in PSPICE software.
As can be seen from the expression of the Gummel-Pool model, nine parameters need to be set in PSpice. However, three of the parameters are directly extended to the parameter values in the IGBT steady-state model, so only 6 parameters are needed to be set, which are $C_2$, $C_4$, $N_{EL}$, $N_{CL}$, $N_F$ and $N_R$.

4. Feasibility Validation under DC Interruption Application
In order to simplify the simulation, the bidirectional disconnection requirements of DC circuit breakers are ignored, and only the IGBT component topology with one-way disconnection function is analyzed by computer simulation. Combined with the IGBT transient simulation model established in Chapter 2, the reliability of the simulation model is further verified. At the same time, the influence of different factors on the turn-off performance of IGBT components under DC turn-off conditions is studied.

In practical engineering applications, each component of circuit breaker and each device in the circuit breaker are connected with each other through copper bar, so there is stray inductance in the circuit, so this is taken into account in the simulation model. Therefore, the simulation circuit of IGBT breaking component is shown in Fig.5.

Table 1 shows the simulation parameters of the device.

| components | name                        | Value          |
|------------|-----------------------------|----------------|
| C1         | Precharge capacitance       | 1.6mF, 2kV     |
| L1         | The load inductance         | 26.5μH         |
| L2         | Energy-dissipating branch   | 80nH           |
| L3         | stray inductors             | 100nH          |
|            | Absorb branch stray inductor|                |
The simulation waveform of the current breaking process is shown in Fig. 6.

![Simulation waveforms](image)

- **a)** Switch off gate voltage waveform
- **b)** Turn off the voltage waveform at both ends of the module
- **c)** Current waveform of turn-off assembly

Fig. 6 IGBT module simulation model turn-off waveform

**5. Conclusion**

In this paper, the research status of IGBT device model is introduced, and the existing model of IGBT device is studied and analyzed. Aiming at the problem that the simulation model of current turnoff device in hybrid DC circuit breaker is lack of DC turnoff condition, a simulation model suitable for circuit analysis is built. It provides some guidance for the current turnoff performance research and topology design of hybrid DC circuit breaker.

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