IGBT SPICE BEHAVIORAL MODEL USING THE HAMMERSTEIN CONFIGURATION

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The behavioral IGBT model for OrCad PSpice simulator is presented. The model is parameterized and it is implemented as a subcircuit in the simulator. The nonlinear DC equations and voltage-controlled capacitor are precisely represented using ABM method, which is resulting in good accuracy. The static I-V characteristics offered by the behavioral model are shown. The tailing of the anode currents simulated by the behavioral model at a constant anode voltage-switching test are given. The good agreement between the simulation and experimental results can be observed in the paper.

Keywords: IGBT behavioral model, SPICE simulator, parameterized macromodel Hammerstein configuration

1. INTRODUCTION

The IGBT is rapidly becoming as the preferred switching device in many power electronic circuits**.** As a consequence, several IGBT CAD models have been recently proposed**,** to describe the operating characteristics of the device [1]-[4]. Roughly speaking, the IGBT models available in literature can be subdivided as either behavioral or physics-based. The behavioral models are based on semi-empirical relations and their results are valid only in a narrow range of operating conditions. The physics-based IGBT models proposed to date, are not easily implemented in circuit simulators, require heavy numerical computations and the knowledge of process parameters, which are not easy to extract from electrical measurements.

The paper presents IGBT SPICE behavioral model, which is built using the configuration of the Hammerstein model [2], [3], consisting of a nonlinear static block followed by a linear dynamic block. The Hammerstein model, shown in Fig.1 represents a realization of the Hammerstein operator

$$H[u(t)] = \int_0^t h(t,\tau) F[\tau, u(\tau)] d\tau, \quad (1)$$

which is simplified to

$$H[u(t)] = \int_0^t h(t-\tau) F[u(\tau)] d\tau \quad (2)$$

for a nonlinear time-invariant system.

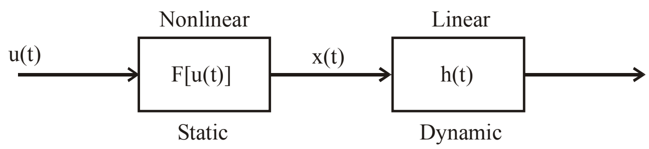

Fig.1. Configuration of the Hammerstein model

In the paper, the nonlinear static block can be simply realized by the static (dc) model for a semiconductor device. This recognition tremendously simplifies the task of parameter extractions, for the static model can be directly obtained from the static I-V characteristics by least-squares methods. Unlike the linear dynamic block in a true Hammerstein model, the dynamic block employed herein is piecewise linear, and is realized by an RC low-pass filter which has different time constants during the turn-on and turn-off transients.

2. IGBT BEHAVIORAL MODEL DESCRIPTION

The output characteristics of the IGBT appear to be similar to the BJT except that the controlling parameter is an input voltage rather than an input current. The transfer characteristic is identical to that of the power MOSFET. This curve is reasonably linear over the wide range of the collector current, becoming nonlinear only at low collector current where the gate-emitter voltage is approaching the threshold. The parameters and characteristics from datasheets are the starting points for determination the parameters for Spice simulator. Most of the model parameters are obtained from the output characteristics.

The proposed IGBT Spice behavioral model is improved Oh model for Saber simulator [2]. The examined model consists of two parts: dc and dynamic (Fig.2). The dc part of the model combines the equations that describe the MOSFET in cutoff, the linear and saturation regions with the equations of a bipolar junction transistor operating in the active mode. The model accounts for high-level injection and the voltage drop in the extrinsic part of the IGBT.

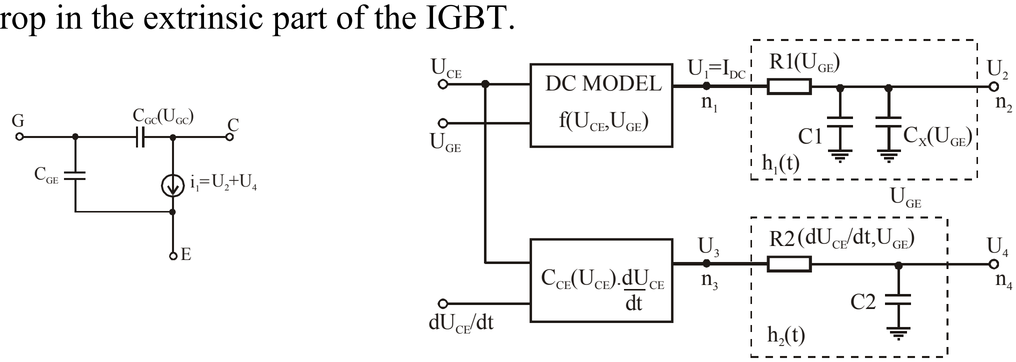

Fig.2

a). Main structure of the behavioral model b). Hammerstein-like structure for I_C

Fig. 2(a) shows the main structure of the behavioral model. The Hammerstein-like structure of the collector current is shown in Fig. 2(b).

2.1. DC MODEL

The dc part is based on an empirical formula for the IGBT collector current given by:

(3)
$$I_C = \begin{cases} 0, & if \quad U_{GE} \le U_{th} \quad or \quad U_{CE} < U_D \\ k.f_2\left[\left(U_{GE} - U_{th}\right)\left(f_1 U_{CE} - U_D\right) - \dfrac{\left(f_1 U_{CE} - U_D\right)^2}{2} \right], \\ if \quad U_{CE} < U_{GE} + U_D - U_{th} \\ k.f_2 \dfrac{\left(U_{GE} - U_{th}\right)^2}{2}, & if \quad U_{CE} > U_{GE} + U_D - U_{th} \end{cases}$$

where

(4)
$$f_1 = a_0 + a_1 U_{GE} + a_2 U_{GE}^2$$

(5)
$$f_2 = b_0 + b_1 U_{GE} + b_2 U_{GE}^2$$

The constants a_i and b_i are determined from the I_C-U_{CE} curves, k is the process transconductance parameter, U_{th} is the threshold voltage and U_D is the voltage drop across the emitter-base junction. The two-correction functions f_1 and f_2 are introduced to avoid the use of the more complex approach that relies on physical modeling [3].

The proposed functions (3) modeled behaviorally more accurately dc collector current than those in [2].

2.2. DYNAMIC MODEL

The collector current is the sum of a component that flows in C_{CG} and C_{GE} and a component i_1, which equals to the sum of values of the voltages U_2 and U_4. That means these voltages have to be translated to currents i_2 and i_4. Therefore the current i_1 consists of two components U_2 and U_4, which are voltage variables having units of current.

From the datasheets, three capacitance curves can be obtained for extraction of C_{CG} and C_{GE}:

(9)
$$C_{ies} = C_{GE} + C_{GC}, \quad C_{res} = C_{GC}, \quad C_{oes} = C_{CE} + C_{GC}$$

where C_{ies} is the input capacitance, C_{res} the reverse transfer capacitance, and C_{oes} the output capacitance. To achieve an accurate description of IGBT's switching waveforms, it is necessary to develop a high precision model for C_{GE}, C_{GC} that exhibit nonlinear variation of the corresponding voltages.

The h_1 block in Fig.2 models the dynamic of the current during the constant collector voltage phase – this is the low-pass filter R_1, C_1 and C_x.

(6)
$$R_1 = \begin{cases} R_{1on} & if \quad U_{GE} > U_{th} \\ R_{1off} & if \quad U_{GE} \le U_{th} \end{cases}$$

(7) $$C_x = \begin{cases} 0 \;\; if \;\; U_{GE} > U_{th} \\ \left(\frac{1-\alpha}{\alpha}\right) C_1 \;\; if \;\; U_{GE} \le U_{th} \end{cases}$$

α accounts for the ratio of the collector currents after and before the rapid decay [4]. C_1 is a constant chosen using t_{don} from the datasheets.

The h_2 block models the time-dependent effects. For a constant C_2, R_2 is modeled as:

(8) $$R_2 = \begin{cases} R_{2on} \;\; for \;\; the \;\; turn-on \;\; transient \\ R_{2off} \;\; for \;\; the \;\; turn-off \;\; transient \end{cases}$$

In present paper the turn-on transient is modeled as $U_{GE}>U_{th}$ and $dU_{CE}/dt\le 0$, and the turn-off transient – as $U_{GE}\le U_{th}$ or $U_{GE}>U_{th}$ and $dUCE/dt>0$. The last two parameters are obtained from simulated U_{CE} waveform [6].

3. IGBT SPICE MODEL IMPLEMENTATION

The behavioral model described above has been developed using ABM method and implemented in the OrCad PSpice simulator. Nonlinear controlled voltage and current sources are used with IF statement to implement the DC model equations (3).

The nonlinear capacitor in the model is replaced by a controlled current source G, which current is defined by

(9) $$I = C(V)dV/dt$$

The time derivative, dV(t)/dt, is modeled by using the DDT( ) function in PSpice. A voltage dependent capacitance can be specified by using a look-up table, or by using a polynomial. In this paper we use look-up table in the ABM expression. This table contains (voltage, capacitance) pairs picked from points on the curve. The voltage input is nonlinearly mapped from the voltage values in the table to the capacitance values. Linear interpolation is used between table values. This voltage dependent capacitance is the multiplied by the time derivative of the voltage to obtain the output current. Fig.3 shows the generic subcircuit of the voltage- controlled capacitance. C_{GC}, C_{CE} are modeled in this manner.

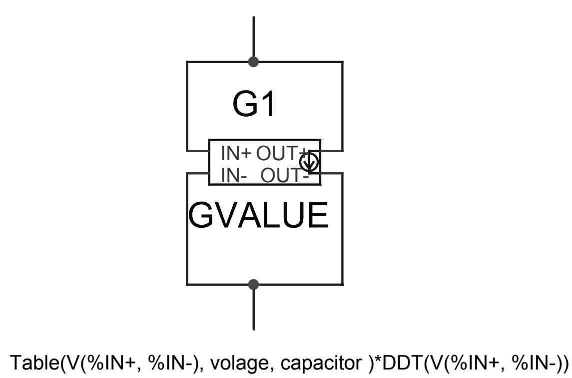

Fig. 3. Nonlinear capacitor with look-up table expression

4. SIMULATION AND EXPERIMENTAL RESULTS

For the verification of the model the type HGTD10N40F1S [7] IGBT is chosen. Fig. 4 shows the static I-V characteristics offered by the behavioral model.

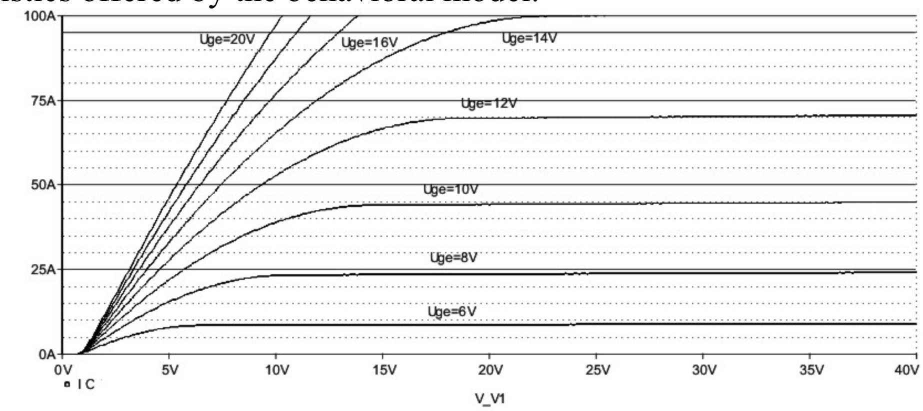

Fig.4. Behavioral model simulated static I-V characteristics

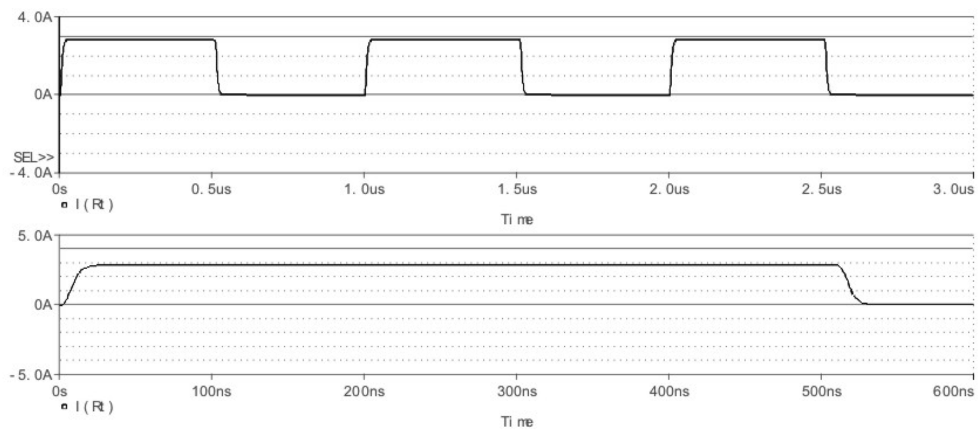

Fig.5. Simulated collector currents at a constant collector voltage switching test

Fig.5 shows the tailing of the collector currents simulated by the behavioral model at a constant anode voltage- switching test. Fig.6 shows one of the transient test circuits at resistor and inductor load and figs.7-8 - the results the collector voltage and the current at different R_1's.

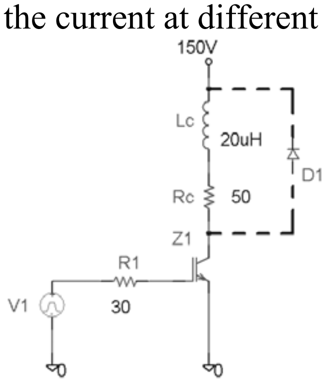

Fig.6. A test circuit at resistor and inductor load

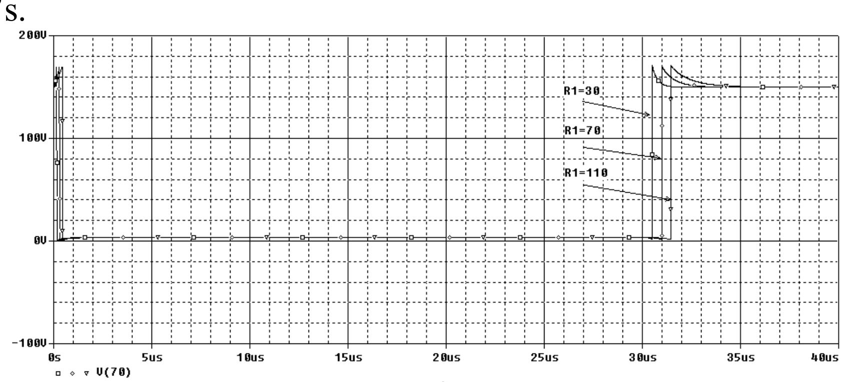

Fig.7. Simulated collector voltage at different R_1's

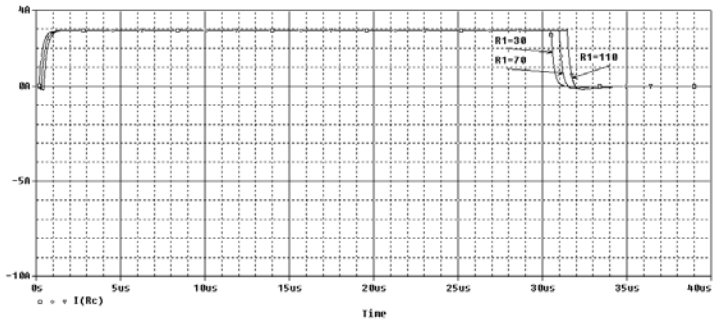

Fig. 8. Simulated collector current at different R_1's

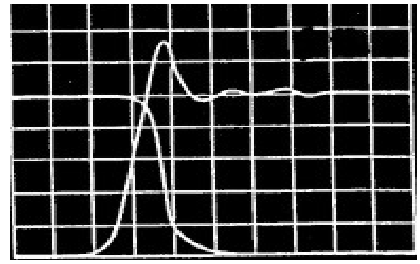

Fig. 9. Test circuit experimental results

The experimental results of the IGBT HGTD10N40F1S connected in the test circuit are given by the following conditions: the supply voltage U_{CC}=50V; a load - R_C=50Ω and L_C=20μH. The switching curves (U_{CE} and I_C) are given in Fig.9 at the resolution U_{CE}=10V/div and I_C=200mA/div.

5. CONCLUSIONS

The behavioral IGBT model for OrCad PSpice simulator is presented. The model is parameterized and it is implemented as a subcircuit in the simulator. The nonlinear DC equations and voltage-controlled capacitor are precisely represented using ABM method, which is resulting in good accuracy. The static I-V characteristics offered by the behavioral model are shown. The tailing of the anode currents simulated by the behavioral model at a constant anode voltage-switching test are given. The good agreement between the simulation and experimental results can be observed in the paper.

A future research direction could be the automatic extraction of the parameters from the datasheets and the inclusion of temperature effects in the IGBT model presented herein.

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