An Improved IGBT Behavioral PSpice Macromodel

Tsvetana Gr. Grigorova[1] and Katya K. Asparuhova[2]

Abstract **– The paper presents an improved IGBT behavioral macromodel suitable for OrCAD PSpice. In the new model, like real IGBTs the collector current slightly increases with the collector-emitter voltage. The developed IGBT behavioral model is parameterized and it is implemented as a subcircuit in the OrCad PSpice simulator. 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 model shows good agreement with measured results and built in PSpice simulator model.**

Keywords **– IGBT behavioral PSpice model.**

I. INTRODUCTION

The IGBT was introduced into the family of power devices to overcome the high on-state loss while maintaining the simple gate drive requirements of power MOSFETs. The IGBT combines both bipolar and MOSFET structures and possesses the best features of both devices types. Because the IGBT has a low power gate drive requirement, a high current density capability and a high switching speed it is preferable to other devices in many power applications and a practical circuit model for IGBT is needed for simulation. Several analytical models have been implemented into circuit simulators (PSpice [1]-[4] and Saber [5]) in recent years. The IGBT models available in literature can be subdivided as either behavioral or physics-based. 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. A significant part of existing behavioral macromodels [5] are physical, based on the internal device structure. The others, considering the semi-empirical relations between terminal voltages and currents, have a poor accuracy and their results are valid only in a narrow range of operating conditions.

However the model still presents some limitations in the saturation region at where the collector current is assumed flat. Real IGBTs show that the collector current slightly increases with the collector-emitter voltage. In this paper, an improvement to the behavioral macromodel, which is presented in [6],[7] is given to overcome this limitation.

[1] Tsvetana Gr. Grigorova is with the Technical University of Sofia, Branch Plovdiv, 61 Sankt Petersburg bul., 4000 Plovdiv, Bulgaria, e-mail: c_grigorova@abv.bg

[2]Katya K. Asparuhova is with the Department of Electronics and Electronics Technologies, Faculty of Electronic Engineering and Technologies, Technical University-Sofia, 8 Kliment Ohridski bul., 1000 Sofia, Bulgaria, e-mail: k_asparuhova@tu-sofia.bg

II. MODEL IMPROVEMENT

The behavioral macromodel, suitable for OrCAD PSpice, is shown in [6],[7]. In this paper the investigations are extended and an improvement made to the behavioral IGBT model is described.

The DC model is based on the empirical formulas for the IGBT collector current detailed described in [7]. It combines the equations that circumscribe the MOSFET in cut-off, the linear and saturation regions with the equations of a bipolar junction transistor operating in an active mode. The model accounts for high-level injection and the voltage drop in the extrinsic part of the IGBT. The next expressions give the collector current in all regions:

$$I_C = \begin{cases} 0, & if \quad V_{GE} \le V_{th} \quad or \quad V_{CE} < V_D \\ k.f_2 \left[\begin{array}{l} (V_{GE} - V_{th})(f_1 V_{CE} - V_D) - \\ -\dfrac{(f_1 V_{CE} - V_D)^2}{2} \end{array} \right] & \\ if \quad V_{CE} < V_{GE} + V_D - V_{th} & \\ k.f_2 \dfrac{(V_{GE} - V_{th})^2}{2}, & \\ if \quad V_{CE} > V_{GE} + V_D - V_{th} & \end{cases} \tag{1}$$

where V_D is the voltage drop across the emitter-base junction, V_{th} is the threshold voltage of the MOSFET and k is the process transconductance parameter [2].

According to [2], [4] and [7] the correction function f_1, dependent on gate-emitter voltage, is introduced in order to make the saturation voltage of MOSFET equal to the corresponding IGBT saturation voltage

$$f_1 V_{CEsat} = V_{GE} + V_D - V_{th} . \tag{2}$$

The correction function is approximated with an appropriate polynomial. The degree of this polynomial depends on the number of the accounted points and required accuracy

$$f_1 = a_0 + a_1 V_{GE} + a_2 V_{GE}^2 . \tag{3}$$

The output current in the saturation region is fitting using the correction function f_2:

$$\frac{I_{Csat}}{f_2} = k \frac{(V_{GE} - V_{th})^2}{2} , \tag{4}$$

where

$$f_2 = b_0 + b_1 V_{GE} + b_2 V_{GE}^2 . \tag{5}$$

There has to be noticed that the correction functions f_1 and f_2 are equal to unity for the low level injection (it means for the

small values of V_{GE}), which case is not observed in the practice.

The polynomial coefficients a_i and b_i of f_1 and f_2 are determined from the I_C-V_{CE} curves. Record the coordinates of the saturation points (V_{CEsat}, I_{Csat}) for three given gate voltages V_{GE}. The value of V_{CEsat} is read at the point where the tangent in saturation region is separated from the curve. Using the systems' solutions the correction functions f_1 and f_2 can be calculated for each value of the gate voltage. The introduction of two-correction functions f_1 and f_2 allows the use of the more complex approach that relies on physical modeling.

From the Eqs.(1), it can be seen that the collector current of the behavioral model is saturated absolutely in the saturation region it is a constant with different collector-emitter voltages and just depends on the gate-emitter voltage only. However the collector current of the real IGBT will not be saturated absolutely in reality. So the behavior model is not accurate enough to describe the saturation characteristics and should be improved in the saturation region [8].

Based on the previous model, two assumptions are made: the first is that the collector current in the saturation region increases linearly with the V_{CE}. The second is that all the reverse extended lines of the collector current in the saturation region intersect the x-axis at the same voltage point V_{Early} [8] (Fig. 1).

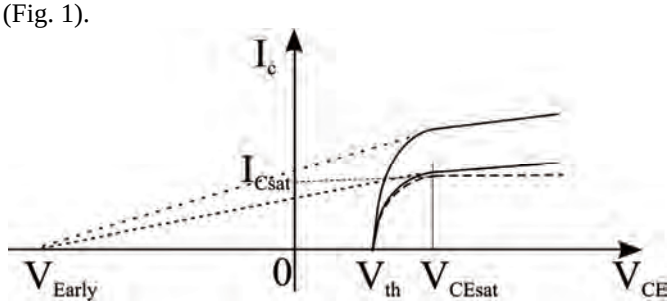

Fig.1. Static I-V characteristics of the improved model

This is similar to the Early voltage in the BJT. Based on these two assumptions, the collector current of the new IGBT model is modeled by adding a linear term to the original model when V_{CE} is greater than V_{th}. The dashed line in Fig.1 presents the original model and the linear term, the solid line presents the new model. From Eqs. (1) the new IGBT model can be written as:

$$I_C = \begin{cases} 0, & if \quad V_{GE} \le V_{th} \quad or \quad V_{CE} < V_D \\ k.f_2\left[\begin{array}{l}(V_{GE}-V_{th})(f_1V_{CE}-V_D)- \\ -\dfrac{(f_1V_{CE}-V_D)^2}{2}\end{array}\right] & \\ if \quad V_{CE} < V_{GE}+V_D-V_{th} & \\ k.f_2\dfrac{(V_{GE}-V_{th})^2}{2}-K(V_{GE})\cdot(V_{CE}-V_{th}), & \\ if \quad V_{CE} > V_{GE}+V_D-V_{th} & \end{cases} \tag{6}$$

where $K(V_{GE})$ represents the slope at a given gate – emitter voltage

$$K(V_{GE}) = \frac{I_{sat}(V_{GE})}{V_{Early}+V_{th}} \tag{7}$$

The voltage V_{Early} is determined in MATLAB through *polyfit* function using I_C *vs* V_{CE}@V_{GE} data. The records are provided by device data sheets or by measurements.

III. IGBT PSPICE MODEL IMPLEMENTATION

The behavioral model described above has been developed using ABM method and implemented in the OrCad PSpice simulator as a subcircuit. The DC part of the IGBT model includes the voltage control current sources GVALUE which implement Eqs. (6), using "IF-THEN-ELSE" operator in PSpice.

The dynamic part of the model is described in detail in [7] and is shown in Fig.2.

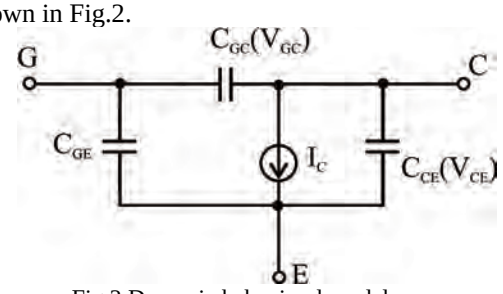

Fig.2 Dynamic behavioral model

From the datasheets, the following capacitance curves can be obtained:

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

where C_{ies} is the input capacitance, C_{res} the reverse transfer capacitance, and C_{oes} the output capacitance. The values of the capacitors can be extracted from the dependence capacitance vs. V_{CE} for $V_{GE}=0$. To achieve an accurate description of IGBT's switching waveforms, it is necessary to develop a high precision voltage-controlled capacitance model that exhibit nonlinear variation of the corresponding voltages. The graphs from datasheet are digitizing using an appropriate program like GetData. In order to consider the dependence of the capacitors on the gate-emitter voltage their values are obtained by scaling on the fitting expression.

A voltage dependent capacitance, using in the dynamic part, can be specified by using a look-up table, or by using a polynomial. In this paper the look-up table in the ABM expression is used. The nonlinear capacitor in the model is replaced by a controlled current source G, which current is defined by

$$I = C(V)dV/dt \ . \tag{4}$$

The time derivative $dV(t)/dt$ is modeled by using the DDT function in PSpice[9]. 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.

The realization in Spice language is with GVALUE "look-up table" voltage control current source:

$$Table\left(V\left(\%IN+,\%IN-\right),voltage,capacitor\right)* \\ DDT\left(V\left(\%IN+,\%IN-\right)\right) \quad (5)$$

C_{GC}, C_{CE} and C_{GE} are modeled in this manner.

The process of the device switching is modeled using a voltage-controlled switch S with parameters: $V_{on}=\{V_{th}\}$, $V_{off}<\{V_{th}\}$, $R_{on}=\{V_{CE(sat)}/I_C\}$ and R_{off} - a very big value corresponding on turn-off transistor.

An advantage of the proposed model is it parameterization. It allows easy implementations of the deferent IGBT types. A part of the preliminarily extracted parameters are included in PARAM operator – these are V_{th}, V_D, k. Other part is included in TABLE operator – these are the digitizing capacitance plot data. The parameters of the voltage-controlled switch are parameterized too.

IV. Simulation and Experimental Results

For the verification of the model the type CM600-24H IGBT is chosen. In the calculation it was assumed that V_{th}=6V, k=102. The simulations are made under following initiation conditions: V_{CE} = 0÷12V, V_{GE} = 7÷12V.

Fig. 3 shows the static I-V characteristics received from the implemented CM600-24H PSpice model and Fig. 4 shows these offered by the behavioral macromodel.

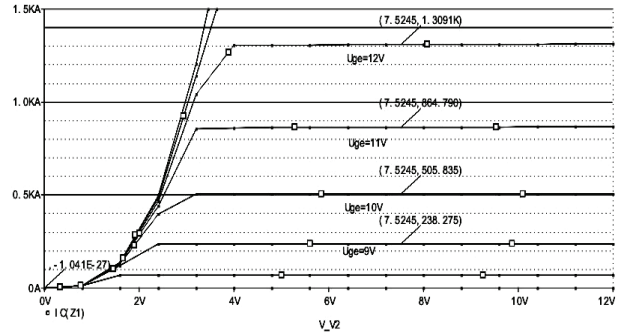

Fig.3. Implemented PSpice model simulated static I-V characteristics for the device CM600-24H

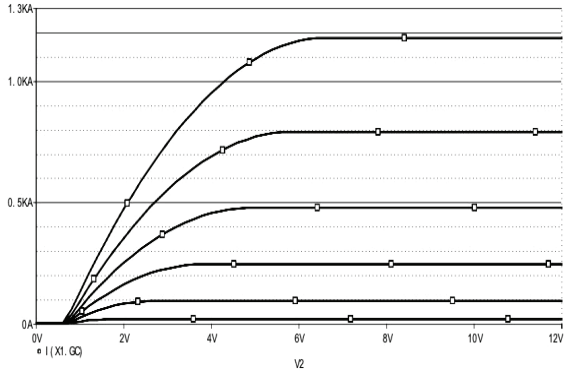

Fig.4. Behavioral macromodel simulated static I-V characteristics for the device CM600-24H

As can be seen in the saturation region the collector current is flat.

Using the Eqs.(6) the improved behavioral macromodel static I-V characteristics are simulated and are presented in Fig.5.

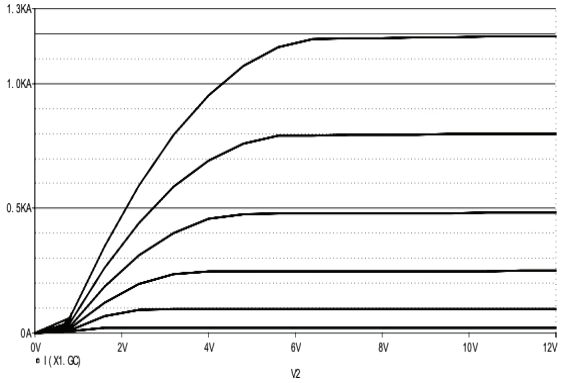

Fig.5. The improved behavioral macromodel simulated static I-V characteristics for the device CM600-24H

It is shown that in the new model, like real IGBTs the collector current slightly increases with the collector-emitter voltage. Fig.6 shows one of the transient test circuits at resistor and inductor load to verify the transient predictions of the proposed model.

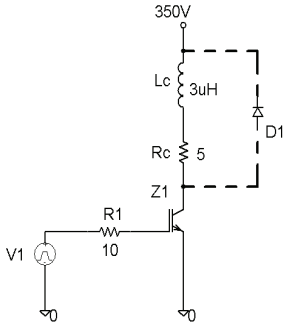

Fig.6. A test circuit at resistor and inductor load

The simulations results of the both models (implemented CM600-24H PSpice model and the proposed behavioral macromodel) are given in the Fig.7.

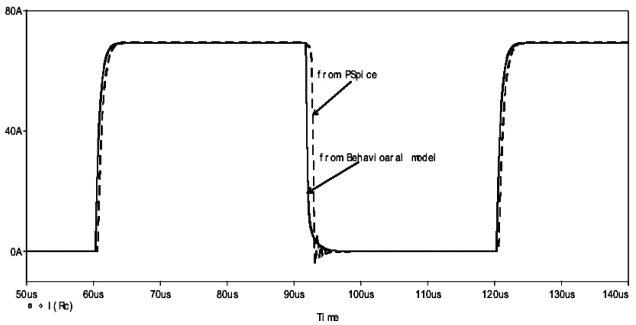

Fig.7 Simulated collector currents at a constant collector voltage-switching test

As seen a very good agreement between transient waveforms is achieved. The error is less than 2%.

On the basis of the proposed macromodel a PSpice behavioral model of IGBT type HGTD10N40F1S is created too [7]. The simulation and experimental results of the IGBT HGTD10N40F1S connected in the test circuit are presented in Fig.8 and Fig.9. The results are given by the following conditions: the supply voltage V_{CC}=50V; a load R_C=10Ω and L_C=10μH.

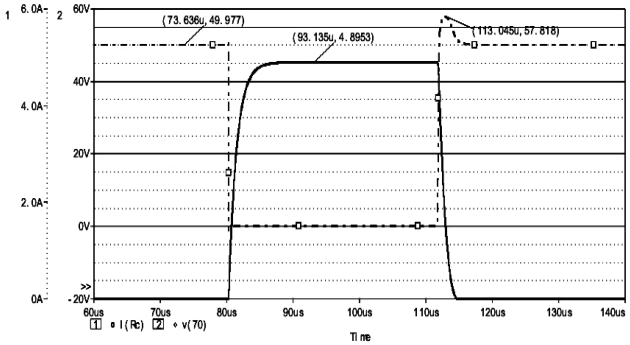

Fig. 8 Transient waveforms using inductive test circuit

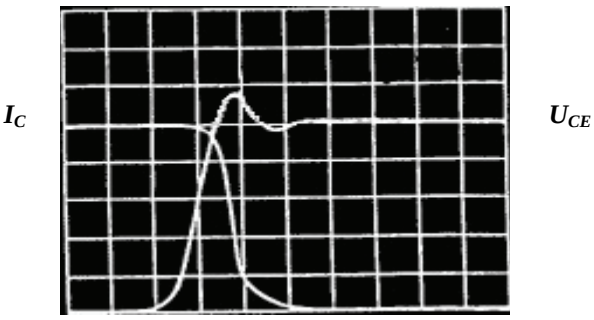

Fig. 9. Test circuit experimental results

The switching curves (U_{CE} and I_C) are given in Fig.9 at the resolution U_{CE}=10V/div and I_C=1A/div. The average error between simulation and experimental results is around 3%.

V. Conclusion

The improved behavioral IGBT macromodel for OrCad PSpice simulator is presented. In the new model, like real IGBTs the collector current slightly increases with the collector-emitter voltage. The developed IGBT behavioral model is parameterized and it is implemented as a subcircuit in the OrCad PSpice simulator. 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 as the average error is around 3%.

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