A QUASI-STATIC MODEL OF THE POWER BJTs

Dzhekov A. Tomislav
Raleva J. Katerina

Cyril and Methodius University – School of Electrical Engineering - Skopje
Republic of Macedonia
tdzhekov@cerera.etf.ukim.edu.mk; catherin@cerera.etf.ukim.edu.mk

ABSTRACT: **A simple physical model for the power BJTs has been developed. It is an extension of the simple piecewise-linear bipolar transistor model, which covers, in addition, the quasi-saturation phenomena - the major observable difference between the characteristics of a power transistor and those of a logic level transistor. To simulate the transient behavior, the charge-control equation is included. Simple analytical expressions for the switching times are derived. The model requires only four parameters and the parameter extraction procedures are straightforward.**

KEY WORDS: **power BJT, quasi-saturation region, quasi-static model**

1. INTRODUCTION

The need for a high voltage capability in the off state and a high current capability in the on state means that a power BJT must have a somewhat different structure than its logic-level counterpart. The modified structure leads to certain differences in the I-V characteristics and in the transient behavior of the two types of devices. The major observable difference is the appearance of a quasi-saturation region in the I-V characteristics of the power BJT, as depicted in Fig. 1. The purpose of this paper is to develop a simple and completely defined quasi-static model, describing the static and dynamic behavior of the power BJT in the forward active, quasi-saturation and hard saturation regions. The breakdown effects and the effects of variation of the common emitter current gain within the forward–active region are not included. For simplicity,

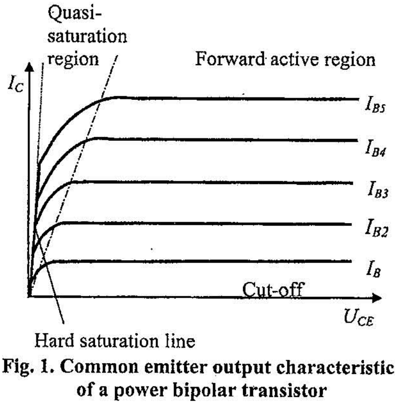

Fig. 1. Common emitter output characteristics of a power bipolar transistor

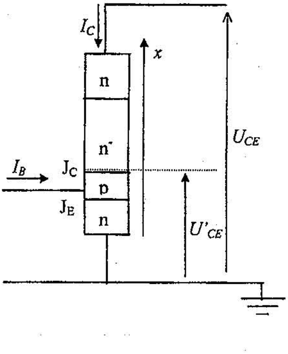

Fig. 2. Common emitter configuration of the power transistor structure

we ignore the effects of the junction capacitances and take $V_{CEsat} = 0$ for hard saturation. To the best of our knowledge, such a model has not been reported so far.

2. QUASI-SATURATION REGION

Consider the power transistor structure in a common emitter configuration, as shown in Fig. 2. Assume fixed base current I_B and a collector-emitter voltage U_{CE} decreasing from some value in the forward active region. Let U'_{CE} denote the potential of the lowest part of the collector drift region.

At the beginning, the pn^{-}- junction denoted by J$_C$ is reverse biased. There is no excess carrier charge in the collector drift region (see Fig. 3-a). When the operating point arrives at the forward-active/quasi-saturation boundary, J$_C$ becomes forward biased and we have injection of holes from the base into the collector drift region. Because of its very low equilibrium majority concentration , the part of the collector drift region in the vicinity of J$_C$ goes quickly into high-level injection. The excess carrier profile obtaines the form given in Fig. 3-b. Assuming low-level injection in the base and high-level injection in the collector drift region, one can write:

$$I_C = -q_o A D_{nB} \frac{\delta n'_B}{\delta x}\bigg|_{x=0^-} = -2 q_o A D_a \frac{\delta n'_C}{\delta x}\bigg|_{x=0^+} \qquad (1)$$

where D_a is the ambipolar diffusion constant of the collector drift region and A is the transistor cross-section. The apparently linear distribution of the excess carriers in the collector drift region is a consequence of the assumption that the collector region is in high level injection and that the hole component of the collector current is negligible. Note that the excess carrier charge located in the base and emitter regions decreases as we move from Fig. 3-a to Fig. 3-b and then to Fig. 3-c. This is understandable since in the quasi-saturation zone a part of the base current is spent to support the excess carrier charge within the collector region (see Fig. 4). The smaller becomes the excess carrier charge in the base region, the smaller will be the slope of the excess carrier concentration in the base and this implies smaller collector current. The excess carrier profiles given in Fig. 3-c correspond to the moment when the operating point reaches the quasi-saturation/hard-saturation boundary. After the moment we enter the quasi-saturation region, the potential of the lowest part of the collector drift region, i.e. $U'_{CE} = U_{BE} - U_{BC}$, becomes approximately equal to zero, as both junctions, J$_E$ and J$_C$, are forward biased. Therefore, if we denote by R_d the resistance of the collector drift region and ignore the voltage drop on the modulated part of the collector drift region, we can use the following approximate equation for U_{CE} within the quasi-saturation zone:

$$U_{CE} = \frac{w_d - x}{w_d} R_d I_C = R'_d I_C \qquad (2)$$

where R'_d is the resistance of the unmodulated portion of the collector drift region (see Fig. 4). Obviously, the slope of the line that separates the forward-active zone from the quasi-saturation zone will be equal to $1/R_d$ (see Fig. 1).

3. MODEL DEVELOPMENT

The following assumptions will be made:

- independent of position excess carriers life-times τ_E, τ_B and τ_C in the emitter, base and collector regions,
- low-level injection in the base and emitter and high level injection in the collector drift region during quasi-saturation,
- the excess carrier concentration $n'_B(0^-)$ at the base/collector boundary can be ignored as relatively small so that (1) reduces to:

$$I_C = q_o A D_{nB} \frac{n'_B(-w_B)}{w_B} = 2 q_o A D_a \frac{n'_C(0^+)}{x} \qquad (3)$$

It can be shown that for large surface recombination velocity s at the emitter contact, as is usually the case, the excess carrier charge in the emitter-region will be given by:

$$Q_E = A L_{PE} q_o \frac{\cosh\frac{w_E}{L_{PE}} - 1}{\sinh\frac{w_E}{L_{PE}}} p_E(-w_B) \qquad (4)$$

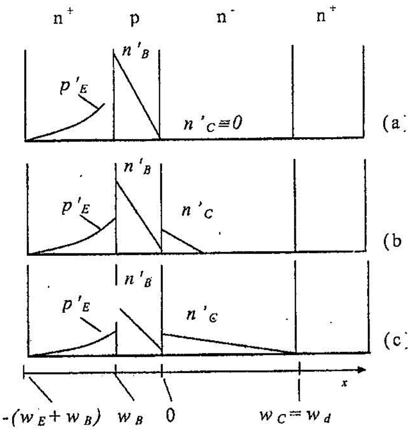

Fig.3 Excess carrier profiles of the power BJT

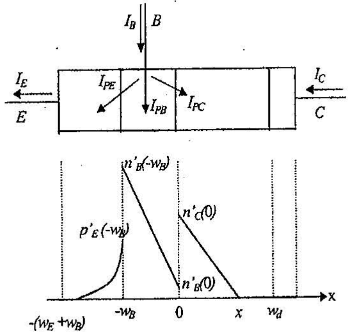

Fig. 4. The base current components and excess carrier distribution under quasi-saturation

On the other hand, the excess carrier charges in the base and collector regions within the quasi-saturation zone will be given by:

$$Q_B = \frac{A w_B q_o n'_B(-w_B)}{2} \qquad (5)$$

$$Q_C = \frac{A x q_o n'_C(0^+)}{2} \qquad (6)$$

For low-level injection in the emitter and base regions (as assumed), the ratio $p'_E(-w_B)/n'_B(-w_B)$ will be independent on the operating conditions. The same must be true for Q_E/Q_B. Thus:

$$Q_E = m' Q_B \qquad (7)$$

where the constant m' is easily found by using the Boltzmann junction law:

$$m' = \frac{2L_{pE}}{w_B}\left(\frac{n_{iE}}{n_{iB}}\right)^2 \frac{N_{AB}}{N_{DE}} \frac{\cosh\frac{w_E}{L_{PE}} - 1}{\sinh\frac{w_E}{L_{PE}}} \tag{8}$$

Combining (3) and (6), one obtains:

$$Q_C = \frac{Ax^2 q_o D_{nB} n_B'(-w_B)}{4D_a w_B} = n'(x) Q_B \tag{9}$$

where:

$$n'(x) = \frac{D_{nB}}{2D_a}\left(\frac{x}{w_B}\right)^2 \tag{10}$$

The base current consists of three components and is given by:

$$I_B = I_{PB} + I_{PE} + I_{PC} = \frac{Q_B}{\tau_B} + \frac{Q_E/(1-\gamma)}{\tau_E} + \frac{Q_C}{\tau_C} \tag{11}$$

where $\gamma = \mathrm{sec}\,h\left(w_E / L_{pE}\right)$ is the ratio between the hole current at the emitter contact and the hole current at the emitter/base-junction. By introducing a time constant τ, whose meaning will becomme clear later, one can define the quantity:

$$Q = Q_B \frac{\tau}{\tau_B} + \frac{Q_E}{1-\gamma}\frac{\tau}{\tau_E} + Q_C \frac{\tau}{\tau_C} = Q_B \frac{\tau}{\tau_B}[1 + m + n(x)]] \tag{12}$$

where

$$m = \frac{m'}{1-\gamma}\frac{\tau_B}{\tau_E}, \qquad n(x) = n'(x)\frac{\tau_B}{\tau_C} \tag{13}$$

and use it as an equiuvalent excess carrier charge of the transistor. Thus in accordance with (11) and (12) is:

$$I_B = \frac{Q}{\tau} \tag{14}$$

From (3) and (5), for the collector current one obtains:

$$I_C = \frac{Q_B}{\tau_{po}}, \qquad \tau_{po} = \frac{Q_B}{I_C} = \frac{w_B{}^2}{2D_{nB}} \tag{15}$$

or

$$I_C = \frac{\tau_B}{\tau_{po}[1 + m + n(x)]}\frac{Q}{\tau} = \beta\frac{Q}{\tau} \tag{16}$$

where β is the common emitter current gain within the quasi-saturation region, with maximal value β_H at the forward-active/quasi-saturation boundary and minimal value β_L at the quasi-saturation/hard-saturation boundary, i.e.:

$$\beta_H = \frac{\tau_B}{\tau_{po}(1+m)}, \qquad \beta_L = \frac{\tau_B}{\tau_{po}\left[1 + m + n(w_C)\right]} \tag{17}$$

Combining (2) and (16), one arrives to the following equation:

$$I_C^{\,2} + \left(\frac{\beta_H}{\beta_L} - 1\right)\left(I_C - \frac{U_{CE}}{R_d}\right)^2 = I_C \beta_H \frac{Q}{\tau}, \quad \text{for } 0 \le U_{CE} \le I_C R_d \qquad (18)$$

which relates the collector current I_C, the effective excess carrier charge Q and the collector to emitter voltage U_{CE} within the quasi-saturation region. Equations (14) and (18), together with

$$I_C = \beta_H \frac{q}{\tau}, \quad \text{for } U_{CE} > I_C R_d \qquad (19)$$

$$U_{CE} = 0, \quad \text{for } Q/\tau \ge I_C/\beta_L \qquad (20)$$

form the required static model of the power BJT.

To obtain a quasi-static dynamic model for the power BJT, we will simply replace equation (14) by the well known charge control equation, i.e.:

$$\frac{\delta Q}{\delta t} + \frac{Q}{\tau} = I_B \qquad (21)$$

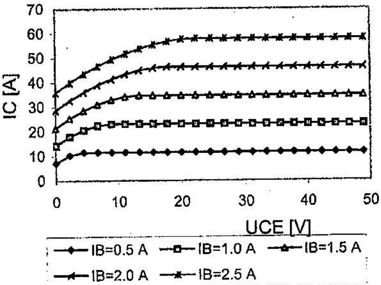

Fig. 5. CE output characteristics of the developed model: $\beta_H = 23.110$, $\beta_L = 14.298$, $R_d = 0.385$ ohm

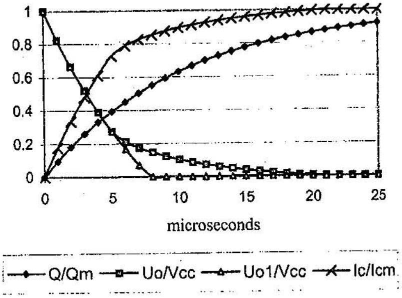

Fig. 6. Turn on transients of an resistively loaded inverter ($\beta_H = 23.110$, $\beta_L = 14.298$, $R_d = 0.385$ ohm, τ=10μs), V_{CC}=50V, R_C=1 ohm I_{B1}=4A

Figs. 5 and 6 are a kind of verification of the developed model. For the sake of comparison, the shape of the output voltage $U_{O1} = U_{O1}(t)$ corresponding to an equivalent transistor without quasi-saturation region is included. Note that $Q_m = I_{B1}\tau$.

The presence of the quasi-saturation zone can have considerable effects on the switching times of the power transistors. Basically, it increases the first transition time t_r, reduces the storage time t_s and increases the last transition time t_f, defined in Fig. 7. Having in mind that $Q(t)$ is an exponential function of time, with time constant τ, one can write:

$$t_r = \tau \ln \frac{Q(\infty) - Q(t_1)}{Q(\infty) - Q(t_2)}, \qquad Q(\infty) = I_{B1}\tau \qquad (22)$$

$$t_s = \tau \ln \frac{Q(\infty) - Q(t_3)}{Q(\infty) - Q(t_4)}, \qquad Q(\infty) = -I_{B2}\tau, \;\; Q(t_3) = I_{B1}\tau \qquad (23)$$

$$t_f = \tau \ln \frac{Q(\infty) - Q(t_4)}{Q(\infty) - Q(t_5)}, \qquad Q(\infty) = -I_{B2}\tau \qquad (24)$$

where $Q(\ )$ is the limit of $Q(t)$ for t . The values of $Q(t_i)$, for i=1, 2, 4 and 5 are easily found by by noting that $U_{CE} = V_{CC} - I_C R_C$, $I_{CM} = V_{CC} / R_C$, by using the definitions in Fig. 7 to find $I_C(t_i)$ and by using the appropriate relation from (18 – 20) to determine the value of $Q(I_C)$ at the corresponding moment t_i. In the case of the academic definition is:

$$t_{ft} = \tau \ln \frac{I_{B1}}{I_{B1} - I_{CM} / \beta_L}$$

$$t_s = \tau \ln \frac{I_{B2} + I_{B1}}{I_{B2} + I_{CM} / \beta_L}$$

$$t_{lt} = \tau \ln \frac{I_{B2} + I_{CM} / \beta_L}{I_{B2}} \qquad (25)$$

Note that $t_{off} = t_s + t_f$ is not influenced by the quasisaturation region.

The proposed power BJT model requires a total of 4 parameters: $\beta_H, \beta_L, \mathrm{R_d}$ and τ. The first two, i.e., β_H and β_L can be obtained by measuring the base and collector current in the forward-active region and at the quasi-saturation/hard-saturation boundary, respectively, and R_d can be determined from the CE output characteristics. To find τ, one can use of expressions (22) or **(24).**

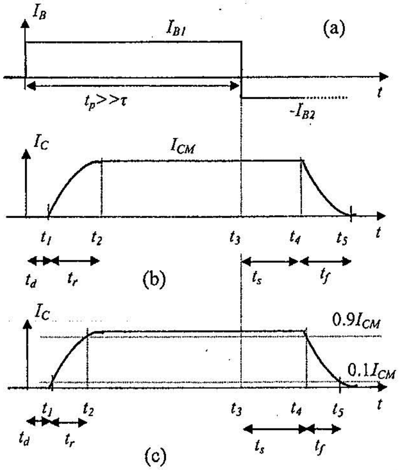

Fig.7. Definitions of the switching times of resistively loaded inverters. (a) Input signal; (b) Academic definition of the switching times; (c) Practical definition of the switching times

4. CONCLUSIONS

A simple, physically based quasi-static model, which simulates very successfully the operating characteristics of the power BJTs within the quasi-saturation region, has been developed. It offers a clear, and somewhat simplified insight in the internal processes and can be used to assess the influence of the various geometrical and physical parameters. In addition, it is characterized by a trivial parameter extraction procedure. As such it is very suitable for educational purposes, as well.

REFERENCES

[1] N. Mohan, T. M. Undeland & William P. Robbins, *Power electronics – converters, applications and design* (New York: John Wiley & Sons, 1995).

[2} N. Talwalkar, P. O. Lauritzen, B. Fatemizadeh &D. Perlman, A power BJT model for circuit simulation, *PESC'96 Rec.*, 1996, 50-55.

[3] B. J. Baliga, *Power semiconductor devices* (New York: PWS Publishing company, 1996).