Advanced representation of power semiconductors using the EMTP

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ABSTRACT

This paper presents a new approach for development and implementation of semiconductors models in the EMTP/ATP. This approach is based on the new ATP option known as Type-94 component. Since ideal semiconductor models are already available as built-in devices, the new method is aimed at developing advanced models. The document presents the application to the diode. Simulation results included in the paper show some of the qualities of the new option and the robustness of the developed diode model. Limitations of the new capability are also discussed.

Keywords: Semiconductors, Modelling, Transient Analysis, EMTP.

INTRODUCTION

The increasing application of solid-state technologies in the power industry is demanding a better understanding of the performance of semiconductors and converters. The digital simulation appears as an interesting solution for evaluating solid-state converters design. Several tools are now available for digital simulation of power electronics systems. One of these tools is the EMTP, a general-purpose program originally developed for simulation of electromagnetic transients in power systems [1]. Since its development was started in the late sixties, the capabilities of this program have been expanded. Presently, this program can be used to simulate most types of transient phenomena in power systems and is becoming a very atractive tool for simulation of power electronics systems [2], [3].

Most semiconductors devices are available in the EMTP as built-in models [4]. However, an ideal model is not an accurate representation in some applications. Internal phenomena must be added in the model since they are critical when switching power losses, conducted EMI and some other effects are of concern. EMTP capabilities can be used to obtain an advanced representation of any semiconductor device. Reference [5] presented the application to represent of an IGBT using TACS capabilities.

This paper presents the application of a new option recently implemented in the ATP version [4], the so-called Type-94 component [6]. It is a new type of nonlinear component that provides an interface between EMTP and a MODELS section [7]. Advantages of this new capability are many : non-delayed interface, MODELS flexibility, steady-state initialization. However, it has also an important limitation, the interface method is based on compensation and only one component, either single or multi-branch, can be included in a network.

Due to limitation of space, only the application to the development of a diode model is presented in this paper. A similar methodology can be used for development and implementation of other semiconductor devices.

The main features of the new option, the Type-94 component, are summarized in the next section. The development of an advanced model for a diode is made gradually. First, the new component is used to represent a diode using a static model [8]. Next, the model is extended to include the reverse recovery [9]. Finally, the dynamic model is completed by adding the forward recovery [10]. Simulation results are presented to illustrate qualities of each model.

TYPE-94 COMPONENT

This new type of nonlinear element provides a non-delayed interface between EMTP and a MODELS section. The Type-94 option allows users to create electrical components and to connect them directly to the nodes of a circuit. A Type-94 component is seen by EMTP as a black box that may be a single or a multi-branch component.

At each time step of the simulation, the model of the component receives from the circuit to which it is connected :

- a Thevenin equivalent of the circuit as seen from the component; this equivalent consists of open-circuit branch voltages, Thevenin resistance matrix and its inverse,
- branch voltages and currents that exits at the previous

time step of the simulation.

A dedicated MODELS section will calculate actual voltages and currents at each branch of the component. Their values will be then included by the EMTP in the solution of the electrical circuit using superposition without performing any iteration. Since the electrical circuit is seen from the Type-94 component as linear, other nonlinear elements connected to the circuit must be separated from the local subnetwork using stub lines.

Type-94 branches are excluded from the initial linear steady-state initialization. However, other branches can be connected in parallel to a Type-94 component for including a simplified representation of the component during steady-state, those branches would be disconnected by means of auxiliar switches before the first time step of the simulation. Voltage and current of each branch of a Type-94 component, which are calculated at time zero of the simulation, can be used by the model of the component for proper initialization.

Corona modelling [11] and representation of circuit breakers [12] are some recent applications of this option.

STATIC MODELLING

This section is aimed at introducing the application of the Type-94 component to the development of a diode model considering the so-called static model, based on the voltage-current characteristic.

Models equations

The diode current is given by any of the following expressions [8]:

$$i_d = I_s\left(\exp\left(\frac{v_d}{V_T}\right) - 1\right) + v_d\, G_{min} \quad (1)$$

for $v_d \geq -5.V_T$, representing the forward polarisation

$$i_d = I_s\left(\exp\left(\frac{v_d}{V_T}\right) - 1\right) + v_d\, G_{min} \quad (2)$$

for $-5.V_T \leq v_d \leq 0$, representing one part of the reverse polarisation.

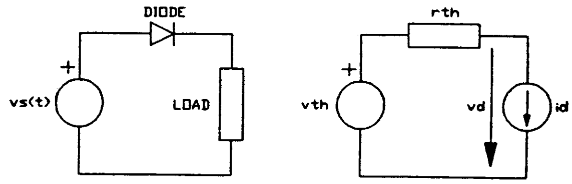
$$i_d = -\, I_s + v_d\, G_{min} \quad (3)$$

for $v_d < -5.V_T$, representing the other part of the reverse polarisation.

In the previous equations, I_s is the saturation current, V_T the thermal voltage and G_{min} the minimum conductance.

ATP implementation

Figure 1 shows the schematic diagram of the circuit which is going to be used to test the performance of this model.



a) Test circuit b) Type-94 representation

Figure 1. Type-94 based diode modelling.

The general equation using the Type-94 component is

$$v_{th} - r_{th}\, .\, i_d = v_d \quad (4)$$

This equation can be rearranged as follows

$$f(v_d) = v_{th} - r_{th}\, .\, i_d - v_d = 0 \quad (5)$$

Then, the procedure to perform a simulation, with an initially desactivated diode, could be the following one:

1) Estimate $v_{d(0)}$.
2) Calculate $i_{d(0)}$ from either (1), (2) or (3).
3) Calculate $f(v_d)$ from (5).
4) If $abs(f(v_d)) > \varepsilon$, the user-specified accuracy, then correct v_d using a Newton-Raphson algorithm

$$v_d(k+1) = v_d(k) - \frac{f(v_d)}{\partial f / \partial v_d}\Big|_{v_d(k)} \quad (6)$$

After solving (6), return to step 2).

5) If $abs(f(v_d)) < \varepsilon$, the resulting v_d and i_d are included by the EMTP to obtain the final state of the circuit using superposition.

Simulation results

Figures 2 and 3 show simulation results corresponding to a circuit with a pure resistive load and an inductive load, respectively. With an inductive load, numerical oscillations can occur; to avoid this problem, inherent to the trapezoidal rule, a snubber circuit is connected in parallel with the diode.

This simple model is fast and efficient, usually only 2 or 3 iterations are to be performed by the Newton-Raphson algorithm for each time-step, except for the first one.

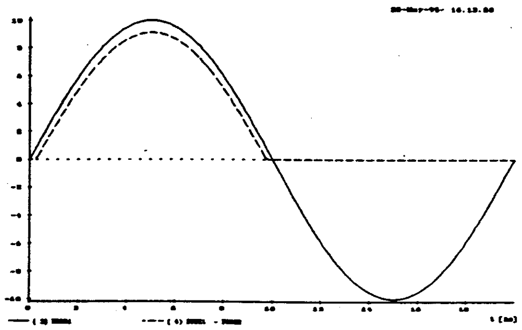
Enhancements to the static model

Other features to be added to this model could be the following ones

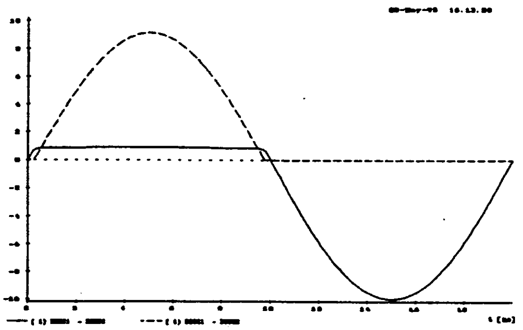
- effect of a series internal resistance R_s
- effect of the emission coefficient n in the diode equation for high-level injection

$$i_d = I_s\left(\exp\left(\frac{v_d}{n\, .\, V_T}\right) - 1\right) + v_d\, G_{min} \quad (7)$$

- effect of the junction breakdown for large reverse bias
- effect of junction and diffusion capacitances for large signal behaviour, see figure 4.

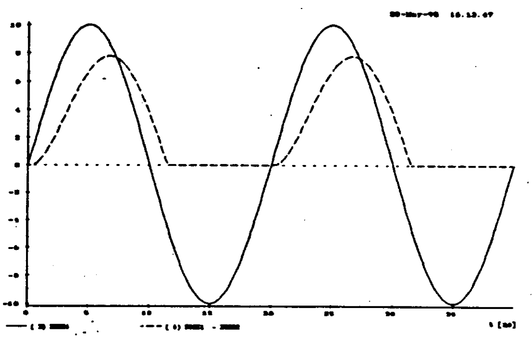


a) Source voltage and diode current

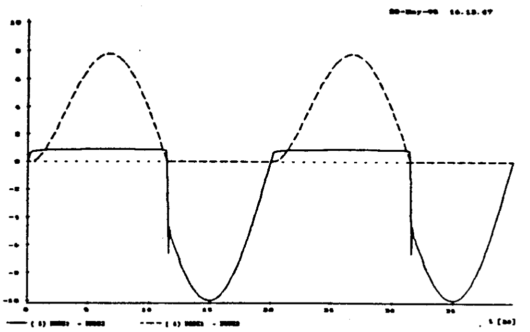


b) Diode voltage and current

Figure 2. Static model with resistive load (R=1Ω).



a) Source voltage and diode current



b) Diode voltage and current

Figure 3. Static model with inductive load (R=1Ω, L=2mH)

The only enhancement which introduces a significant change in the former procedure is the addition of a capacitance whose value is dependent of the diode voltage. This problem is not discussed in this section, but it will be considered in the dynamic model which will be presented later.

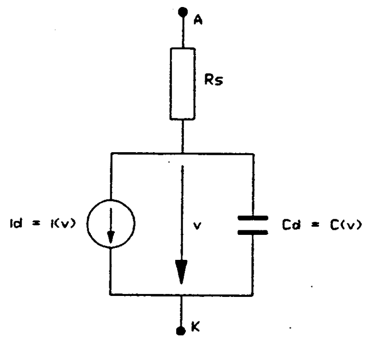


Figure 4. Improved static model.

DYNAMIC MODELLING FOR REVERSE RECOVERY

The reverse recovery is a transient mode which occurs when a forward conducting diode is turned off quickly and the internally stored charges are evacuated during a reverse current period with a high reverse voltage.

Model equations

The former model includes the effects of the charge storage during reverse recovery operation but it does not provide correct operation for the diode during the transient process. A simple model presented in [9] is an extension of the basic charge control model derived from the semiconductor charge transport equations.

The dynamic performance of the diode is described by means of the charge control continuity equation

$$\frac{dq_M}{dt} + \frac{q_M}{\tau} - \frac{q_E - q_M}{T_M} = 0 \tag{8}$$

being τ the carrier lifetime and T_M the transit time.

The first term represents the charge variation with respect to time, the second is the recombination with lifetime τ and the third is the diffusion of charge.

The current in the junction is given by

$$i_M = \frac{q_E - q_M}{T_M} \tag{9}$$

The model is completed with the equation of the injected charge level at the junction

$$q_E = I_{s0} . \tau . \left(\exp\left(\frac{v_d}{n . V_T}\right) - 1\right) \tag{10}$$

where I_{s0} is the saturation current.

As for the static model, n and V_T are the emission coefficient and the thermal voltage, respectively.

ATP implementation

The continuity equation is modified as follows

$$\frac{dq_M}{dt} = \frac{q_E}{T_M} - q_M\left[\frac{1}{\tau} + \frac{1}{T_M}\right] \tag{11}$$

Then, by applying the trapezoidal rule of integration, the equation becomes

$$q_M(t + \Delta t) = k_E \cdot q_E(t + \Delta t) + HIST_q \tag{12}$$

with

$$k_E = \frac{\Delta t}{T_M \cdot (2 + \Delta t . k_M)}$$

$$HIST_q = \frac{2 - \Delta t . k_M}{2 + \Delta t . k_M} \cdot q_M(t) + k_E \cdot q_E(t)$$

$$k_M = \frac{1}{\tau} + \frac{1}{T_M}$$

The implementation of this new model, using the Type-94 component, is based on the same principle that was used with the static model. The proposed method does not include steady-state initialization and the diode is supposed to be desactivated at the starting time t=0. The complete procedure can be summarized as follows:

1) Estimate $v_{d(0)}$.
2) Calculate $q_{E(0)}$ from (10).
3) Calculate $q_{M(0)}$ from (11).
4) Calculate $i_{d(0)}$ from (9), ($i_d = i_M$).
5) Calculate

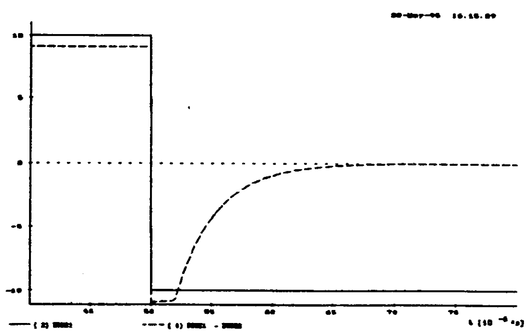
$$f(v_d) = v_{th} - r_{th} . i_d - v_d$$

6) If abs(f(v_d))>ε, then correct v_d using a Newton-Raphson algorithm. After solving (6) return to step 2).
7) If abs(f(v_d))<ε, the resulting v_d and i_d are included by the EMTP to obtain the final state of the circuit using superposition.

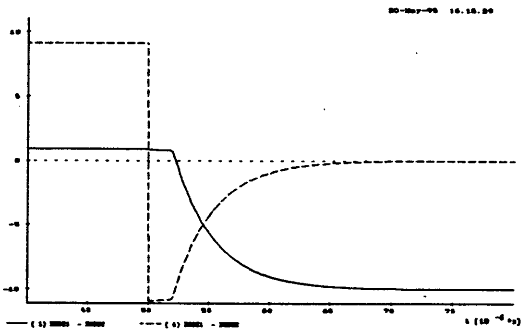
Simulation results

Figures 5 and 6 show simulation results with two different source voltages and loads. Plots of figure 5 depict the reverse recovery of a diode when a pure resistive load is fed from a DC source whose voltage is suddenly inverted. The plots show waveforms of the reversal for the diode voltage and the decrease of the current during reverse recovery.

Plots of figure 6 show the performance of the diode with an inductive load fed from an AC source. As for the static model, a RC snubber circuit is needed in parallel with the diode to avoid numerical oscillations.

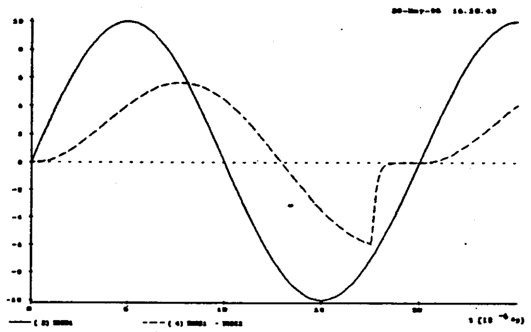


a) Source voltage and diode current

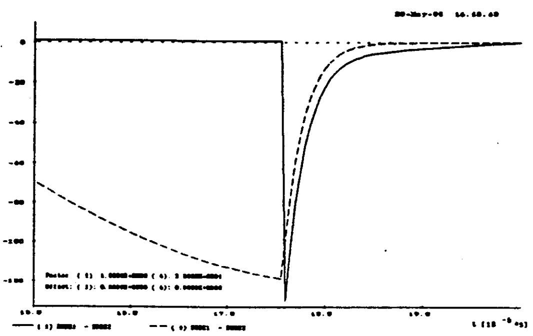


b) Diode voltage and current

Figure 5. Reverse recovery with DC source and resistive load (V_{DC}=10V, R=1Ω).



a) Source voltage and diode current



b) Diode voltage and current

Figure 6. Reverse recovery with AC source and inductive load (V_{AC}=10V-50kHz, R=1Ω, L=5μH).

COMPLETE DYNAMIC MODEL

Model equations

During a rapid switch from off-state to on-state, a high forward voltage builds up across the diode due to the initial low conductance. This process is known as forward recovery. According to [10] voltage and current are related by the following equation

$$v_M = \frac{V_T \cdot T_M \cdot R_{m0} \cdot i_d}{q_M \cdot R_{m0} + V_T \cdot T_M} \quad (13)$$

being R_{m0} the initial resistance.

Under very high current level, a new equation is to be included in order to represent the carrier recombination with a new saturation current I_{sE}, lower than I_{s0},

$$i_E = I_{sE} \cdot \left(\exp\left(2 \cdot \frac{v_E}{V_T}\right) - 1 \right) \quad (14)$$

To complete the model, the series internal resistance R_s and the junction capacitance C_d must be included. The capacitance has a non-linear behaviour that depends on junction voltage v_E

$$C_d = C_{j0} \cdot \left(1 - \frac{2 \cdot v_E}{\phi_0}\right)^{-m} \quad (15)$$

for $2.v_E < 0.5.\phi_0$, or

$$C_d = 0.5^{-(m+1)} \cdot C_{j0} \cdot \left(\frac{2 \cdot m \cdot v_E}{\phi_0} - 0.5 \cdot (m - 1) \right) \quad (16)$$

for $2.v_E \geq 0.5.\phi_0$.

being C_{j0} the zero-bias junction capacitance, ϕ_0 the built-in potential and m the grading coefficient.

The complete diode model will be based on equations (8), (9), (10), (13), (14), (15), (16) plus the following set

$$i_j = C_j \cdot \frac{d(2 \cdot v_E)}{dt} \quad (17)$$

$$v_d = 2 \cdot v_E + 2 \cdot v_M + R_s \cdot i_d \quad (19)$$

$$i_d = i_E + i_M + i_j \quad (18)$$

ATP implementation

Only two dynamic equations are present in this model, the first one is the continuity equation, the second one is the junction capacitance equation. The continuity equation is modified by applying the trapezoidal rule as with the previous model, see equation (12).

The new model implementation is performed using a procedure simular to those used previously. Assuming the diode is initially desactivated, the implementation of the complete model with forward and reverse recoveries can be made by using the following procedure :

1) Estimate $v_{Et(0)}=2.v_{E(0)}$ at time t = 0.
2) Calculate $q_{E(0)}$ from (10).
3) Calculate $q_{M(0)}$ from (12).
4) Calculate $i_{M(0)}$ from (9).
5) Calculate $i_{E(0)}$ from (14).
6) Calculate C_d and i_j using the following approach

$$i_j(t + \Delta t) = 0.5 \cdot C_d \cdot \Delta t \cdot v_{Et}(t + \Delta t) + HIST_i \quad (19)$$

with

$$HIST_i = i_j(t) + 0.5 \cdot C_d \cdot \Delta t \cdot v_{Et}(t)$$

7) Calculate $i_{d(0)}$ from (18).
8) Calculate $v_{M(0)}$ from (13).
9) Calculate

$$f(v_E) = v_{Th} - r_{Th} \cdot i_d - R_s \cdot i_d - 2 \cdot v_M$$

The last two steps are exactly the same as for the previous models.

Simulation results

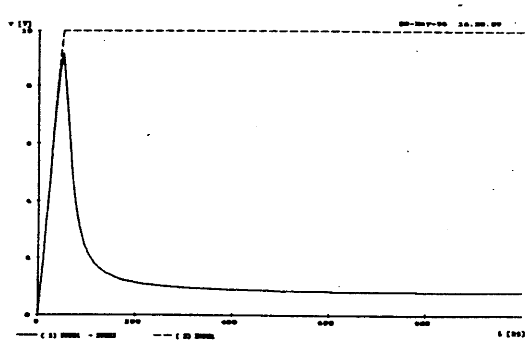
Simulation results presented in figures 7 and 8 show the performance of the complete model. Results depicted in figure 7 correspond to a case with a resistive load fed from a DC source. The initial voltage slope is not infinite, a ramp instead of a step has been used. The forward recovery is presented for a diode with $R_{m0}=500\Omega$, $\tau=5\mu s$ and $T_M=1\mu s$.

Figure 8 show results with an inductive load fed from an AC source. This case was simulated using the following diode parameters : $R_{m0}=500\Omega$, $\tau=10\mu s$, $T_M=0.2\ \mu s$. These waveforms show a lower forward recovery, this is due not only to the new parameters but to the shape of the supply voltage too.

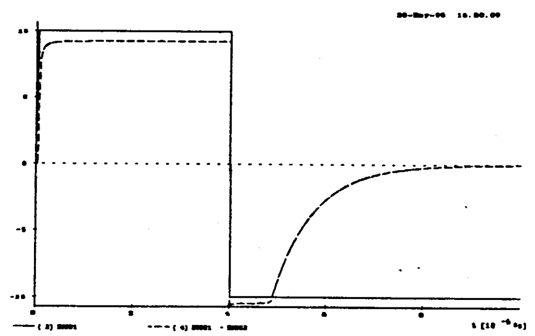
CONCLUSIONS

The Type-94 component is a very flexible and powerful ATP capability that can be used to develop and implement new semiconductor models without changing the program code. With the new approach, semiconductors are treated as branches instead of switches. Although the paper has presented the application to a single-branch device, the procedure can be easely extended to multi-branch devices, such as SCR, BJT, GTO or IGBT. Development and implementation of other semiconductor models could follow a procedure simular to that presented in this document.

An important limitation of this capability is related to the interface method used by the present version of the Type-94 component, based on compensation. Only one nonlinear component, either single or multi-branch, can be included per network. The option makes easy the development of semiconductor libraries using DATA MODULARIZATION technique [13], [14]. This is an

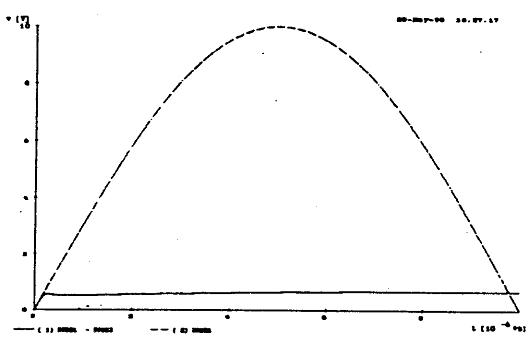


a) Forward recovery

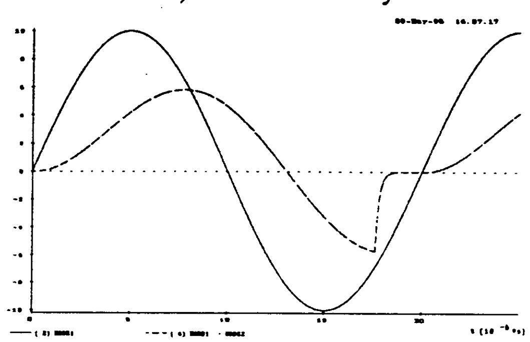


b) Source voltage and diode current

Figure 7. Complete model with DC source and resistive load (V_{DC}=10V, R=1Ω).



a) Forward recovery



b) Source voltage and diode current

Figure 8. Complete model with AC source and inductive load (V_{AC}=10V-50kHz, R=1Ω, 5μH).

interesting feature that makes more atractive this new capability.

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