Volume 40, Number 1, 2000

ACTA TECHNICA NAPOCENSIS
Electronics and Telecommunications

ELECTRONIC DEVICES MODELING BY FUZZY LOGIC INTERPOLATOR

Gabriel OLTEAN, Mihaela GORDAN
Technical University of Cluj-Napoca, Str. C. Daicoviciu No.15,
Gabriel.Oltean@bel.utcluj.ro , *Mihaela.Gordan@bel.utcluj.ro*

Abstract: An important application of fuzzy logic systems is the approximation of non-linear curves. This application has been successfully used in device modeling based on their response to one input stimulus; an example is the I(V_D) characteristic modeling for a diode [3]. In this paper we propose a generalisation of the fuzzy modeling from [3] to the modeling of a three-dimensional surface y(x_1, x_2) and an application of this fuzzy modeling principle to describe the electronic devices behaviour, when this behaviour depends on two input variables. As an example we consider the current dependence on voltage and temperature for the rectifier diode, I(V_D, T), and the transistor characteristic I_C (V_{BE}, V_{BC}).

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I. INTRODUCTION

Due to the increasing complexity of analogue integrated circuits (million of transistors/chip), the classical analysis/simulation techniques that use differential equations for every non-linear device model become unsuitable due to the large computational time required for simulation. One way to reduce this computational complexity is to use simpler models. This can be done either by macromodeling [1], either by finding very simple models for the non-linear devices.

An attractive technique for non-linear device modeling is fuzzy logic, due to the property of fuzzy logic systems of being universal approximators [2], while needing few simple operations to perform this task. Such a fuzzy modeling principle of an electronic device considering one input variable and one output variable is presented in [3], where a model for the characteristic I(V_D) of a rectifier diode is built.

In this paper we propose a new modeling principle of the electronic devices, considering two input variables and one output variable, using fuzzy systems. In order to illustrate our modeling principle we present a fuzzy model for the I(V_D, T) characteristic of the 1N4148 rectifier diode and a fuzzy model for the I_C(V_{BE}, V_{BC}) characteristic of a bipolar transistor.

To develop our fuzzy logic models we will use numerical data and mathematical formulas offered by the reference circuit simulator SPICE [4]. It must be mentioned that we didn't try to obtain a more accurate model than SPICE but a model that is simpler than SPICE model, easier and faster to simulate.

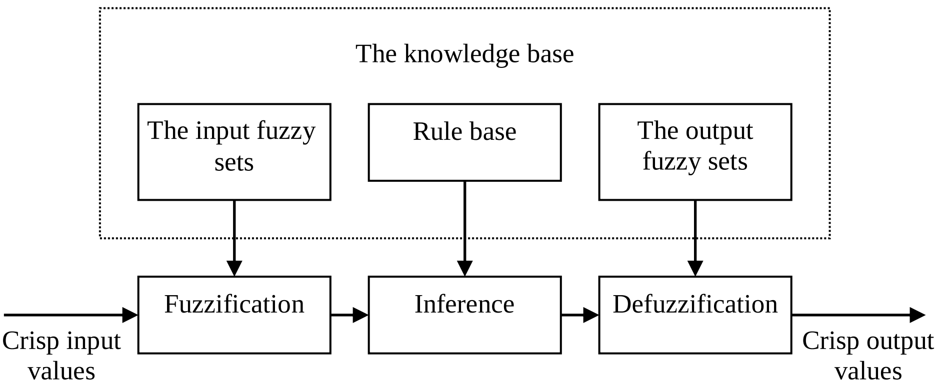


Figure 2.1 The block diagram of a fuzzy logic system

Our proposed method is faster than classical methods that solve differential equation systems, because it uses a small number of very simple mathematical operations: min, max, prod. In addition, due to the interpolation ability of fuzzy systems, it is possible to circumvent the need for rigorous mathematical modeling.

II. THE MODELING PRINCIPLE

The following considerations are made on the block diagram of a fuzzy logic system shown in Figure 2.1.

The **knowledge base** contains:

1. Fuzzy sets corresponding to each input respective output linguistic variable.
2. A rule base that contains control rules of "if then" format:

IF <premise> THEN <conclusion>

In the "premise" part, appear the input linguistic variables and in the "conclusions" part appear the output linguistic variables.

The **fuzzification interface** performs the translation of the crisp values of the input variables into their corresponding input fuzzy sets. These sets are the inputs of the inference block and they define the activation degree of every rule from the rule base.

In the **inference block**, the rules are activated with a certain degree corresponding to the fuzzification interface. This degree shows the conclusion weight in the final conclusion of the system.

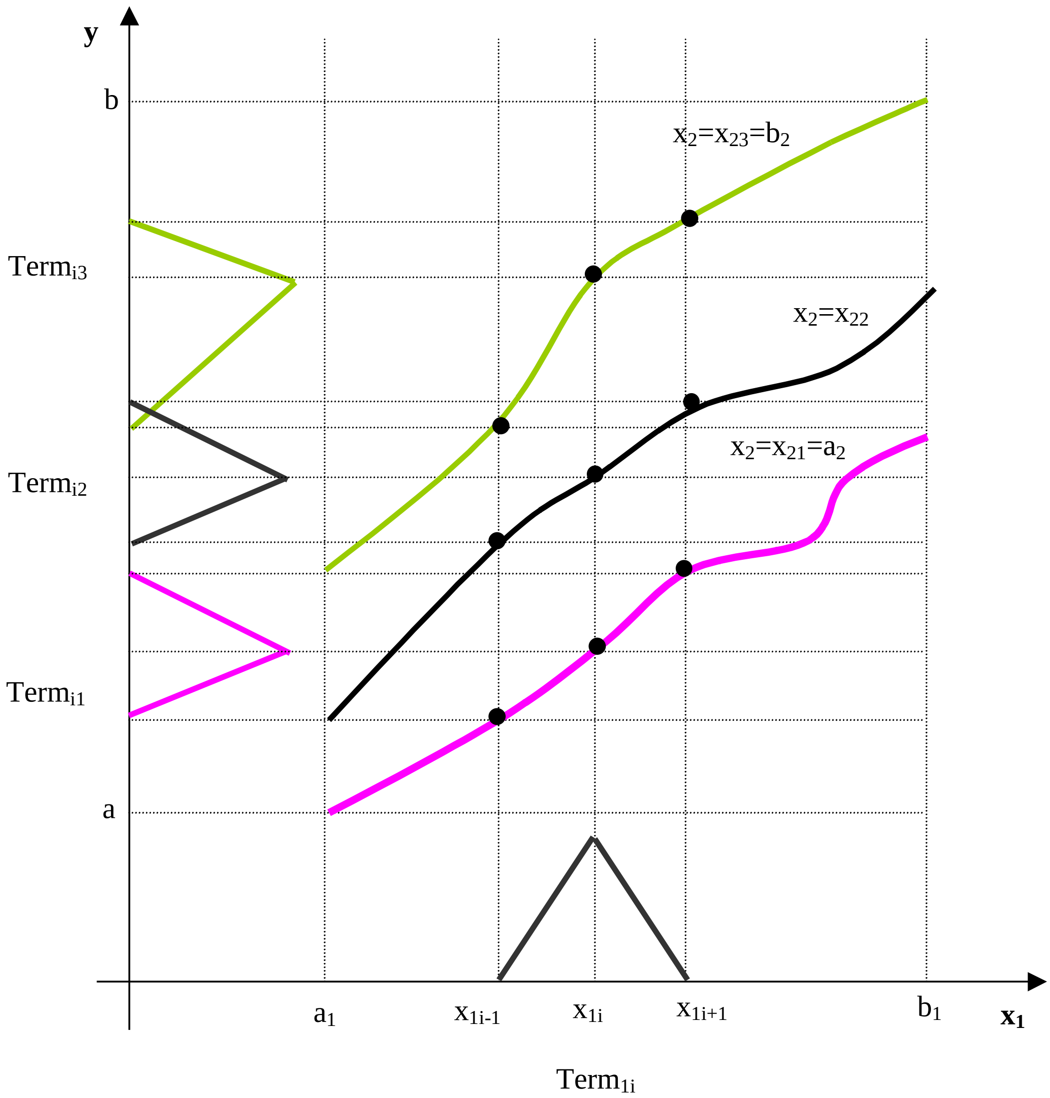


Figure 2.2. Fuzzy modeling of the $y(x_1, x_2)$ surface

The **defuzzification interface** transforms the fuzzy sets generated by the inference block into the crisp values of the output variables.

Our modeling principle is based on the following affirmation: any curve that wiggles can be covered by a finite number of fuzzy patches. In addition, it's known that a fuzzy patch can be defined by a fuzzy rule. The rough rules give big patches and the fine rules give small patches. If we want to create a more precise fuzzy system, we have to use more fuzzy sets. A few wide fuzzy sets may give a rough cover of a non-linear systems [5].

To develop fuzzy model for electronic devices considering two input variables and one output variable we propose the **following modeling principle**: we must design a fuzzy logic system with two inputs: x_1 and x_2, and one output y, that approximates the surface $y(x_1, x_2)$ illustrated in Figure 2.2. To do this, we choose a number of pairs of input values (x_{1i}, x_{2j}) on the surface as interpolation points; for these co-ordinates, the output y of the fuzzy system must match exactly the surface, and between them we will have a fuzzy interpolation of the surface. We denote the number of points chosen on the x_1 range by N; the number of points on the x_2 range is 3 (constant). So, we have 3N pairs of points for interpolation: (x_{1i}, x_{2k}), i=1…N and k=1…3.

After choosing these pairs of co-ordinates, we read from the $y(x_1, x_2)$ surface the y co-ordinate for each (x_{1i}, x_{2k}), i=1…N and k=1…3:

$$y_{ik} = y(x_{1i}, x_{2k}), i = 1\ldots N \text{ and } k = 1\ldots 3.$$

The values x_{1i}, i=1…N, will be used to define the triangular fuzzy sets that cover the universe of discourse for the variable x_1 $[a_1, b_1]$. The values x_{2k}, k=1…3, will be used to define the triangular fuzzy sets that cover the universe of discourse for the variable x_2: $[a_2, b_2]$. The values y_{ik}, i=1…N, k=1..3, will be used to define the triangular fuzzy sets that cover the universe of discourse for the variable y: [a, b].

- **The fuzzy sets for the input variable x_1** are considered to be triangular; having N interpolation points for x_1, x_{1i} for i=1…N, we will define N fuzzy sets: two right triangles, denoted by $Term_1$ with the co-ordinates $(x_1, \mu)=\{(x_{11}, 0),(x_{11}, 1),(x_{12}, 0)\}$ and $Term_N$ with the co-ordinates $(x_1, \mu) = \{(x_{1N-1}, 0), (x_{1N}, 1), (x_{1N}, 0)\}$, placed on the range extremes, and N-2 triangles, denoted by $Term_i$, with the co-ordinates $(x_1, \mu) = \{(x_{1i-1}, 0), (x_{1i}, 1), (x_{1i+1}, 0)\}$, for i=2…N-1.

- **The fuzzy sets for the input variable x_2** are considered to be also triangular having 3 interpolation points x_{2k} for k=1…3. We will define 3 fuzzy sets: two right triangles, denoted by $Term_{21}$ with the co-ordinates $(x_2, \mu)=\{(x_{21}, 0),(x_{21}, 1),(x_{22}, 0)\}$ and $Term_{23}$ with the co-ordinates $(x_2, \mu) = \{(x_{22}, 0), (x_{23}, 1), (x_{23}, 0)\}$, placed on the range extremes, and another triangle, denoted by $Term_{22}$, with the co-ordinates $(x_2, \mu) = \{(x_{21}, 0), (x_{22}, 1), (x_{23}, 0)\}$. These fuzzy sets are plotted in Figure 2.3.

- **The fuzzy sets for the output variable y** are triangular too; we will have 3N interpolation points for y, y_{ik} for i=1…N and k=1…3 that will define at most 3N fuzzy sets. The fuzzy sets generation for the output variable y is performed independently for each set of points y_{ik}, i=1…N and k constant, i.e., for varying i and the same k. For a given k, we define two right triangles, denoted by $Term_{1k}$ with the co-ordinates $(y, \mu)=\{(y_{1k}, 0),(y_{1k}, 1),(y_{2k}, 0)\}$ and $Term_{Nk}$ with the co-ordinates $(y, \mu) = \{(y_{N-1\,k}, 0), (y_{Nk}, 1), (y_{Nk}, 0)\}$, placed on the range extremes, and N-2 triangles, denoted by $Term_{ik}$, with the co-ordinates $(y, \mu) = \{(y_{i-1\,k}, 0), (y_{ik}, 1), (y_{i+1\,k}, 0)\}$, for i=2…N-1. After finding all 3N fuzzy sets (***terms***) for y, we eliminate those terms that appear more than once (if $Term_{ik}$ is identical to $Term_{pq}$, then one of them is eliminated; is no point on memorising the same fuzzy set twice).

- **The fuzzy** rules should establish the connection between **linguistic** input variables and linguistic output variable. The fuzzy rules to model the $y(x_1, x_2)$ surface in Figure 2.2. are on the following format:

IF $x_1 = Term_{1i}$ AND $x_2 = Term_{21}$

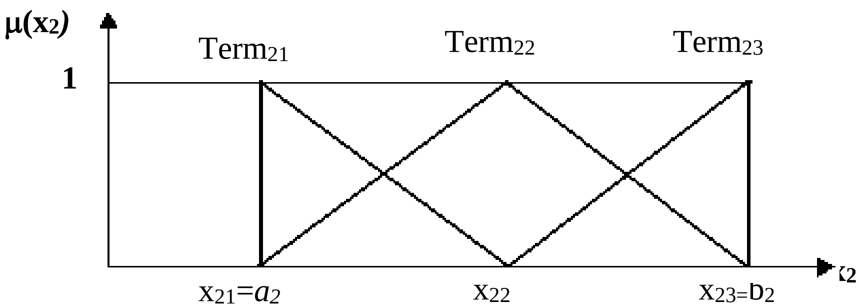


Figure 2.3. The fuzzy sets for the input variable x_2

THEN $y = Term_{i1}$

IF $x_1 = Term_{1i}$ AND $x_2 = Term_{22}$
THEN $y = Term_{i2}$

IF $x_1 = Term_{1i}$ AND $x_2 = Term_{23}$
THEN $y = Term_{i3}$

The fuzzy inference identifies the rules that will be applied to the current situation and will computes the fuzzy set of the output linguistic variable. Our experience shows that trying to create a fuzzy model for a process that has a non-linear characteristic, we can get optimal results using MAX/MIN or MAX/PROD inference method. In the following examples we use MAX/PROD inference method.

A very important step is to choose the defuzzification method. The objective of a defuzzification method is to obtain the crisp value that best represents the fuzzy value of the output variable. The Centre-of-Maximum (COM) and Centre-of-Gravity method are used in most fuzzy logic implementations [6]. In our applications, we used the COM method because it has a high computational efficiency. COM first determines the most typical value for each term and then computes the best compromise of the fuzzy logic inference result. In addition, an important property of the COM method is continuity because the “best compromise” can never jump to a different value for a small change of the inputs [6]. This means that an infinitesimally change of an input variable can never cause an abrupt change in the output variable.

As one can see our proposed fuzzy system is a Mamdani type. There is also possible to use a zero order Takagi-Sugeno system. The fuzzy sets for the inputs are the same with the ones presented above. For the output variable can be considered singleton fuzzy sets. Each output fuzzy sets $Term_{ik}$ (Figure 2.2.) will be replaced with a singleton fuzzy sets with the support equal with the y_{ik} (centre of the $Term_{ik}$). Using the Takagi-Sugeno fuzzy system the results must be identical to those obtained using Mamdani system described above. In this paper we used Mamdani system because we implemented our

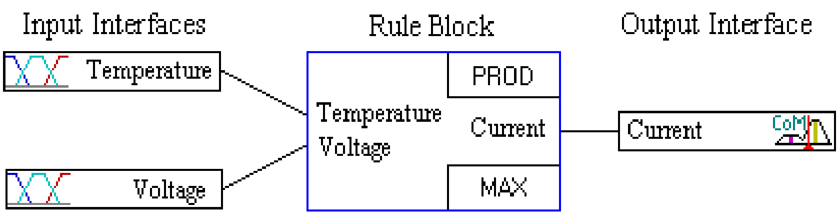
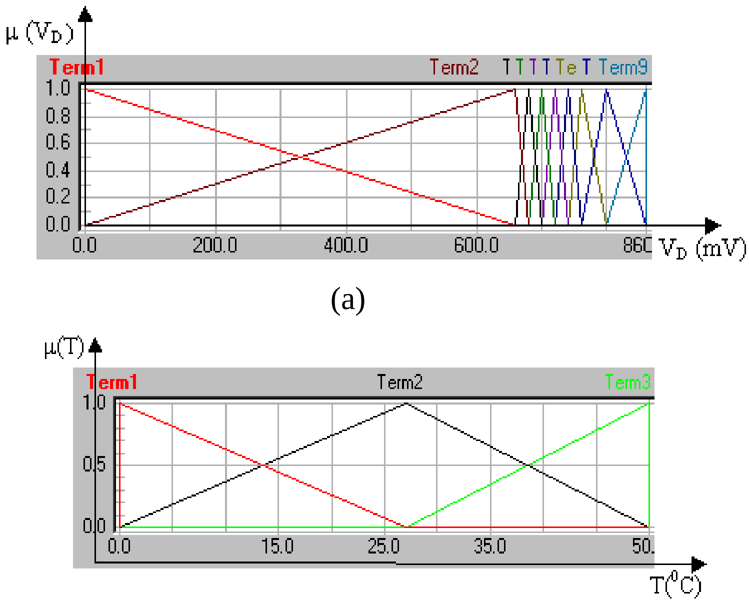


Figure3.1. Fuzzy system for the rectifier diode modeling



(a)

(b)

Figure 3.2. (a) The fuzzy sets for the *Voltage* input variable;
(b) The fuzzy sets for the *Temperature* input variable

system in FuzzyTech simulation software which can not support Takagi-Sugeno systems.

III. EXAMPLES: DIODE AND TRANSISTOR MODELING

In this section we present the models obtained for the 1N4148 rectifier diode and for the bipolar transistor, using our modeling principle.

First we make a briefly presentation of the **fuzzy system used for the rectifier diode**. The two inputs of the system are the voltage across diode V_D and the temperature T; the output of the system is the current I through the diode (Figure3.1.)

Our fuzzy system will define the diode behaviour in the direct region. According to 1N4148-diode practical applications, we selected the input voltage range from 0mV to 860mV because the latter represent the diode breakout voltage corresponding to the nominal temperature (27^0C). To obtain the numerical data

necessary to develop our model we perform a parametric analysis using SPICE simulation, with three values (0^0C, 27^0C and 50^0C) for the temperature. We picked out the temperature limits 0^0C and 50^0C because we supposed that they cover the practical working region. Thus we derived the ranges $[0, 50]^0$C and [0, 650]mA for the input temperature and for the output current respectively.

The fuzzy sets for the input and output variables were chosen according to the algorithm presented in Section 2 and they are presented in Figure3.2 and Figure3.3., as they are plotted in the FuzzyTech software used for simulating fuzzy logic systems.

To build the fuzzy system we define the system rules according to the considerations made in Section 2.
The three-dimensional surface representing the result obtained using our fuzzy model is presented in Figure 3.4.

The **second proposed model** is used for depicting $I_C=I_C(V_{BE}, V_{BC})$ characteristic of the bipolar transistor. I_C is defined as collector current, V_{BE} as base-emitter voltage and V_{BC} as base-collector voltage.

We use a fuzzy system similar to the one proposed for the diode, the input variables being V_{BE} and V_{BC} and the output variable being I_C. To create the model we used numerical data obtained by PSPICE simulation. We consider that I_C does not depend on V_{BC} in normal active region and on V_{BE} in reverse active region.

According to the these considerations, we obtained the same fuzzy sets for both input variables (Figure 3.5.)

The fuzzy sets of the output variable are plotted in Figure 3.6. The off region is described by a singleton fuzzy set (Term8) corresponding to crisp value zero.

In the saturation region, the value of the collector current is determined by another circuit element (for instance a resistor) found in the collector circuit. Therefore, we did not create the fuzzy model for covering this region, our model being proposed just for bipolar transistor as a device.

Figure 3.7 plots the graphical result of the model.

IV. VALIDATION OF THE MODELS

In order to verify the performance of the proposed modeling procedure of a surface and its suitability to electronic devices modeling, we focused on the results obtained for the two examples given in Section 3 and we compared these results with those generated by SPICE (considered as reference in the CAD modeler's scientific world).

The main comparison criterion was the maximal error between fuzzy logic simulation results and Spice simulation results.

For example, in the case of the diode characteristic model, $I(V_D,T)$, since this "worst case error" always appear between the interpolation points, we computed the error for the temperature values 13.5 ^{0}C and 38.5 ^{0}C and for the voltage values 670 mV, 690 mV, 710 mV, 730 mV, 750 mV, 780 mV and 830 mV. For all the resulting pairs of values, we estimated the maximal relative error, as shown in Table 1. We can see that the largest error is 56% and the smallest error is 4.5%. However, since the large error values appear only for small currents, these errors can be neglected.

Comparable errors have been obtained in the case of transistor modeling. These errors can be further reduced if we use more fuzzy sets for surface description. Still, since one of the main advantages of the fuzzy model compared to Spice model is the computational speed, we cannot

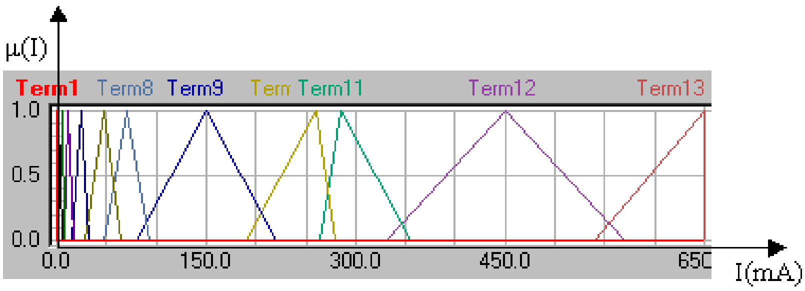


Figure3.3. The fuzzy sets for the *Current* output variable

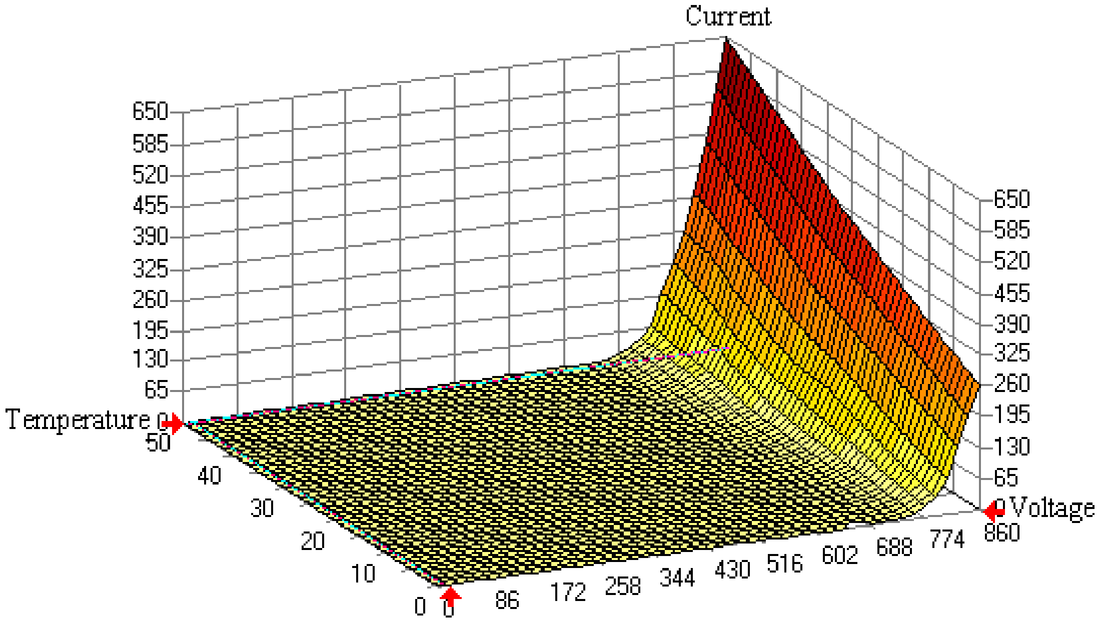


Figure3.4. The I(V_D, T) fuzzy model

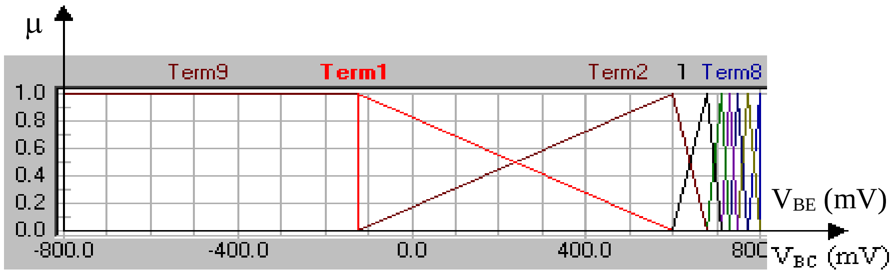


Figure3.5 The fuzzy sets for the V_{BE} and V_{BC} input variables

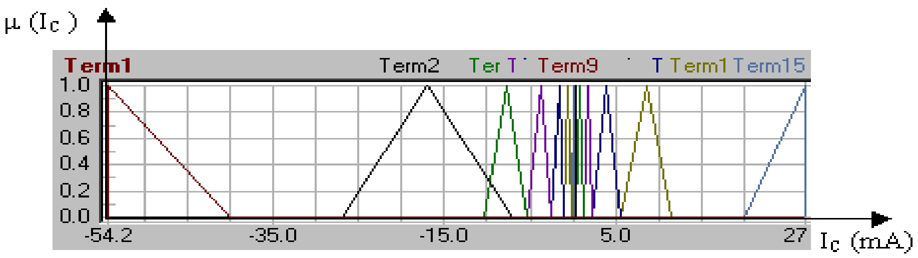


Figure 3.6. The fuzzy sets for the I_C output variable

increase the number of fuzzy sets too much, because this will increase the computational requirements.

Another important advantage of the fuzzy model compared to the Spice model is its ability of computing the output for any pair of (continuous) input values in a single simulation step once the model is built, while doing this in Spice requires a new parametric analysis each time we want to set the input considered as parameter to a value we didn't considered in our current parametric analysis.

V. CONCLUSIONS

We proposed in this paper a new modeling procedure for the electronic devices, using two inputs one output fuzzy systems. Starting from the idea that a curve can be covered with fuzzy patches we covered a three-dimensional surface with fuzzy patches adding one more

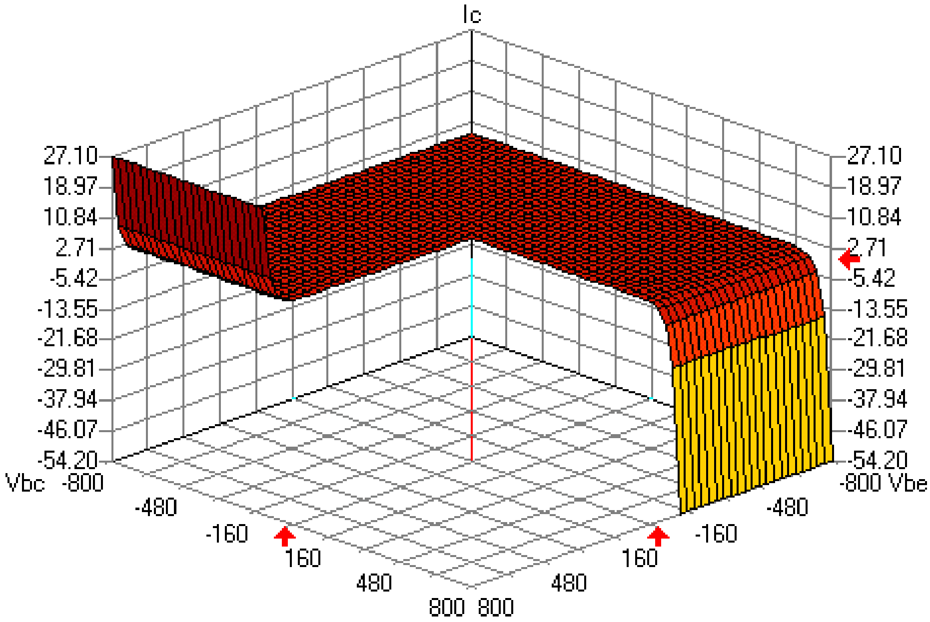


Figure3.7 The $I_C = I_C(V_{BE}, V_{BC})$ fuzzy model

input to the fuzzy system. Then, considering that this surface is a family of curves, we built a fuzzy modeling principle for the electronic devices and we presented two particular applications. The derived results can be easily understood because they are three-dimensional plotted. An advantage of the modeling procedure is that we can circumvent the need for the rigorous mathematical modeling. In addition, the fuzzy modeling procedure requires only simple mathematical operation: MIN, MAX and PROD. That means that for the fuzzy model of an electronic device, the computation time will be shorter than for a mathematical model based on differential equations of the same device. To obtain a more accurate fuzzy model it is enough to increase the number of the fuzzy sets and fuzzy rules of the model. Therefore we believe that using fuzzy logic very accurate models for any electronic devices can be created.

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Table 1

Input voltage [mV]	**Current values from SPICE simulation [mA]**		**Current values from fuzzy simulation [mA]**		**The relative error ε_i (%)**	
	T = 13.5⁰ C	**T = 38.5⁰ C**	**T = 13.5⁰ C**	**T = 38.5⁰ C**	**T = 13.5⁰ C**	**T = 38.5⁰ C**
670	1.2	3.71	1.88	5.32	56	43
690	2.51	7.68	3.1	11	23	43
710	4.49	15.66	5.32	22.12	18	41
730	8.68	31.09	11	38.24	26	22
750	16.62	58.96	22.12	72.74	33	23
780	49.07	135.66	69.66	160.66	41	18
830	200.74	367.15	226.76	383.76	12	4.5

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