FUZZY MODELLING OF THE VOLTAGE TRANSFER CHARACTERISTIC FOR THE SIMPLE TERNARY INVERTER

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Abstract: Given the fact that the design and especially the manufacturing of some ternary circuits are now possible, using the basic ternary circuit to design more complex ones becomes a necessity. The simulation using models lead to savings of time and money in the design process. The aim of the paper is to model, using fuzzy logic systems, the voltage transfer characteristic for simple ternary inverter, the basic circuit in the design of complex ternary circuits. The obtained fuzzy system provides a correct voltage transfer characteristic.

Keywords: *Fuzzy logic system, ternary inverter, voltage transfer characteristic.*

I. INTRODUCTION

In the ternary logic there are three logical values “0”, “1” and “2” logic. In ternary circuits, each signal wire can transmit more information than compared with binary circuits, leading to the decreasing of the connection number. The circuits which are using ternary logic can be more economical than their binary counterparts [1].

They are few basic ternary circuits: inverter (three types of inverter: simple, positive, negative), maximum, and minimum. Combining two or more basic circuits, more complex ternary circuits can be designed, both combinational and sequential. Recent works show that the design of ternary circuits (ternary clocks [2], ternary memory cells [3], [4]) is a current area of interest.

Simulations are usually the first step in checking the circuit design. However, circuit level simulations can be expensive in terms of computation, especially if the circuits are large and require multiple types of analysis (in time, in frequency). An alternative is to use circuit models, models which should be very accurate.

Fuzzy logic, used to model the operation of the circuit, is a superset of conventional Boolean logic. Intelligent systems based on fuzzy logic consider that an object belongs to a fuzzy set with different degrees, generating the flexibility to interpretation of different situations [5].

In literature fuzzy descriptions are used to model different circuits. In [6] the modeled circuits are: simple transconductance operational amplifier, Miller operational transconductance amplifier, and common-emitter stage. In [7] an active second order low pass filter is modelled. Binary circuits are modelled too; in [8] a series of CMOS logic gates being modelled using ANFIS (adaptive neuro-fuzzy inference system). However, for ternary circuits, fuzzy models have not yet been developed.

Our paper describes the development of a fuzzy logic model for a simple ternary inverter. The model eliminates the need for an actual simulator of the circuit.

The paper is structured as follows: Section II presents the modelling procedure; Section III describes the followed steps for modelling of the voltage transfer characteristic; Section IV presents the results and Section V concludes the paper by summarizing the advantages of the proposed model.

II. MODELLING PROCEDURE

The aim of the paper is the functional modelling of a ternary circuit. The modelling process combines data from SPICE simulation and fuzzy functions from MATLAB.

Inverter is the most fundamental part in any logic, even for higher radices especially for radix-*3* (ternary) [9]. In Yoeli-Rosenfeld algebra [10] are three types of ternary inverters: simple ternary inverter (STI), positive ternary inverter, and negative ternary inverter. From all three types of inverters, only STI provides to output all three logic levels. Because of that, the circuits chosen to be modelled is STI. Table 1 represents the truth table of STI.

Table 1. The truth table of STI

Input [Logic levels]	0	1	2
Output [Logic levels]	2	1	0

First, the circuit was simulated in SPICE (OrCad). In this way, data used for modelling process are provided. The inverter was designed and simulated at transistor level. Based on data provided by SPICE, and with the help of MATLAB functions (*genfis, anfis, writefis, evalfis*), a fuzzy system was developed.

The block diagram of the modelling procedure is shown in Figure 1.

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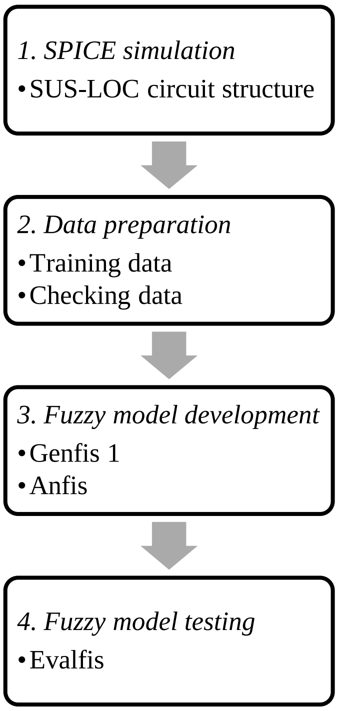

Figure 1. Block diagram of the modelling procedure

III. MODELLING OF THE VOLTAGE TRANSFER CHARACTERISTIC

The voltage transfer characteristic (VTC) shows the static behavior of the circuit, and gives the response of the circuit (output voltage) to specific input voltages. The steps used to model the VTC for STI are presented below.

III.1. SPICE simulation

The ternary inverter is simulated in SPICE and is performed using the SUS-LOC structure. SUS-LOC was patented by E. D. Olson in 2000, and has been developed for multivalent circuit design [11].

The transistor level circuit of STI, simulated in SPICE, is shown in Figure 2.

The operating principle of STI is based on the operating principle of binary inverter. The enhancement transistors, p-type *Q3*, and n-type *Q4*, are in on state alternatively, so that the logic levels "0" (*VSS*=*0*V) and "2" (*VDDH*=*5*V) are obtained.

In addition to the binary inverter, the ternary one has a second circuit branch, carried out with the depletion mode transistors, *Q1*, respectively *Q2*. The new branch is supplied with *2.5*V (*VDDL*, logic level "1"). When the input is "1", both transistors are on and the *VDDL* voltage is transferred to the output.

In SPICE, for transistors were used models in 90 nm technology.

III.2. Data preparation

The next step in the modelling process is to collect simulation data and to prepare it, for further use in MATLAB.

This objective is fulfilled with the help of a Time Domain (Transient) simulation from SPICE. The simulation provides *620* data pairs, based on the step size of the simulator. The step size was chosen so that it would ensure good precision, without providing an overwhelming amount of data. A pair consists of a value of the input voltage and the corresponding output voltage. Few sample data pairs are presented in Table 2, where the input data are considered the values of the input voltage and the output data are considered the values of output voltage.

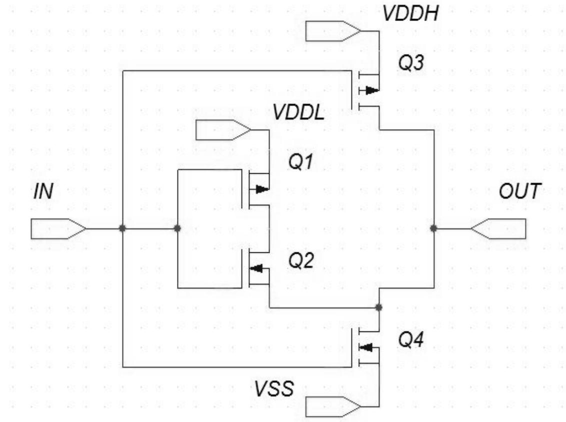

Figure 2. Simple ternary inverter – transistor level

The dataset obtained from the SPICE simulation is then transferred to MATLAB. Data pairs were divided into two subsets: *75*% (*465* pairs) is considered as training data, and the remaining *25*% (*155* pairs) will be the checking data. This ratio between training and checking data samples is recommended by [12], as it ensures proper learning capabilities.

Table 2. Sample data pairs

Input voltage [V]	Output voltage [V]
0.025001	4.889199
0.075002	4.889373
0.175004	4.886665
0.375007	4.880497
0.625019	4.866138
0.87503	4.836346
1.125042	4.751179
1.31229	4.218394
1.523082	3.317835
1.610597	3.046816
1.740639	2.752001

III.3. Fuzzy model development

In order to model the VTC in MATLAB, the following functions are used: *genfis1*, *anfis* and *writefis*. The initial fuzzy system is generated using *genfis1*. This function generates a single-output Sugeno-type fuzzy inference system, using the training data. The number of rules was specified to *10*. The input voltage of the simple ternary inverter is considered the input variable of the fuzzy system, while the output voltage is the output variable. Both input and output variables share the same number of membership functions, namely ten.

The parameters of the initial fuzzy system are tuned using the training data set and the *anfis* function. The final fuzzy system is then saved, for further use, using *writefis*.

The training process is set to stop after *1000* epochs.

III.4. Fuzzy model testing

The fuzzy system is tested using the *evalfis* function. *Evalfis* function is used to evaluate the output of our fuzzy system for a given input.

IV. RESULTS

The results obtained during and to the end of the modelling process are presented.

The waveforms of the input and output voltages (one period) obtained after SPICE simulation are provided in Figure 3. For example, for *0*V input voltage an output voltage equals with *4.8875*V is obtained; for *2.5*V input voltage, *2.3982*V for the output voltage is obtained.

Figure 4 presents the *10* fuzzy sets of the input variable. The universe of discourse is between *0* and *5*. The type of the fuzzy sets is generalized bell-shaped (*gbell*).

The evolution of the error (*rmse* – root mean square error) in the training and checking datasets for the first *300* epochs is presented in Figure 5. The error decreases steeply in the first epochs (*1 - 100*), and then slowly stabilizes, over the next epochs.

Figure 6 a) shows the VTC of the simple ternary inverter, obtained from the reference dataset, as well as from the fuzzy system. The differences between the two voltage transfer characteristics are highlighted in Figure 6 b), which depicts the point-by-point error. The magnitude of the error has a maximum of *26* mV and it doesn't affect the recognition of the logic level.

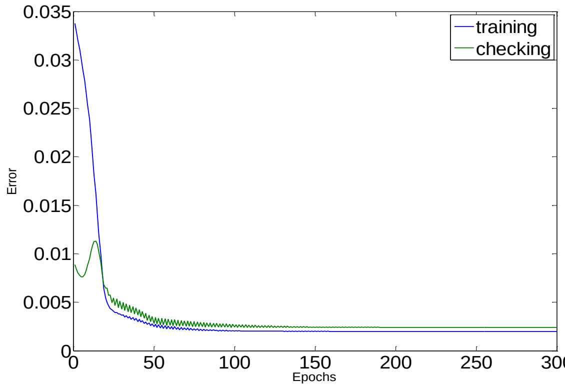

Figure 5. The evolution of rmse in the training and checking datasets, over 300 epochs

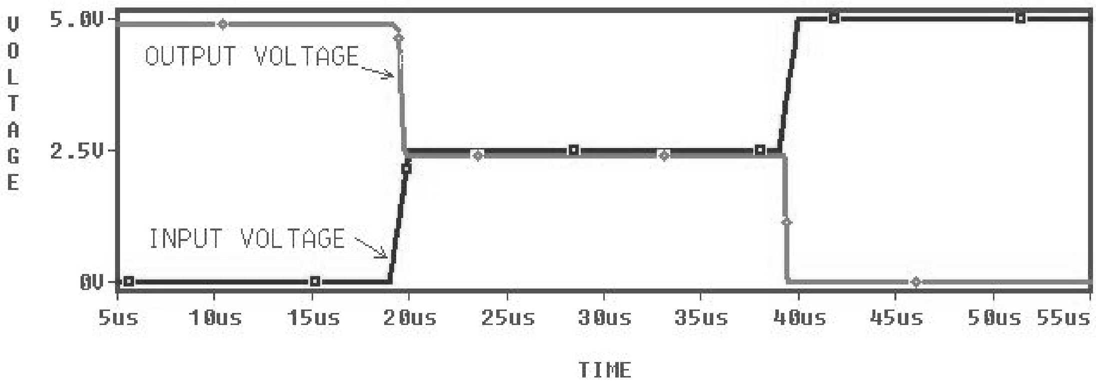

Figure 3. Waveforms: input voltage, output voltage

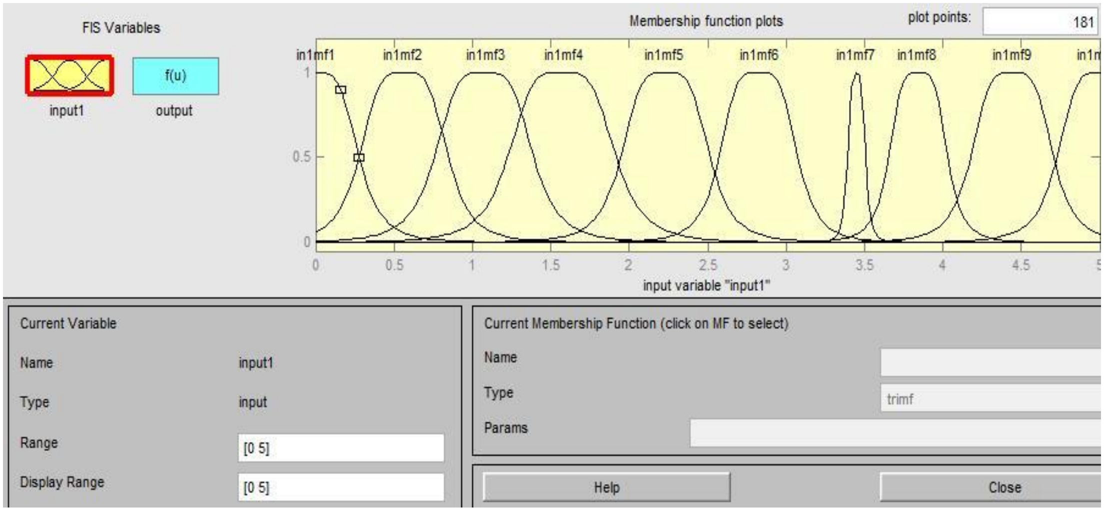

Figure 4. Fuzzy sets for the input variable

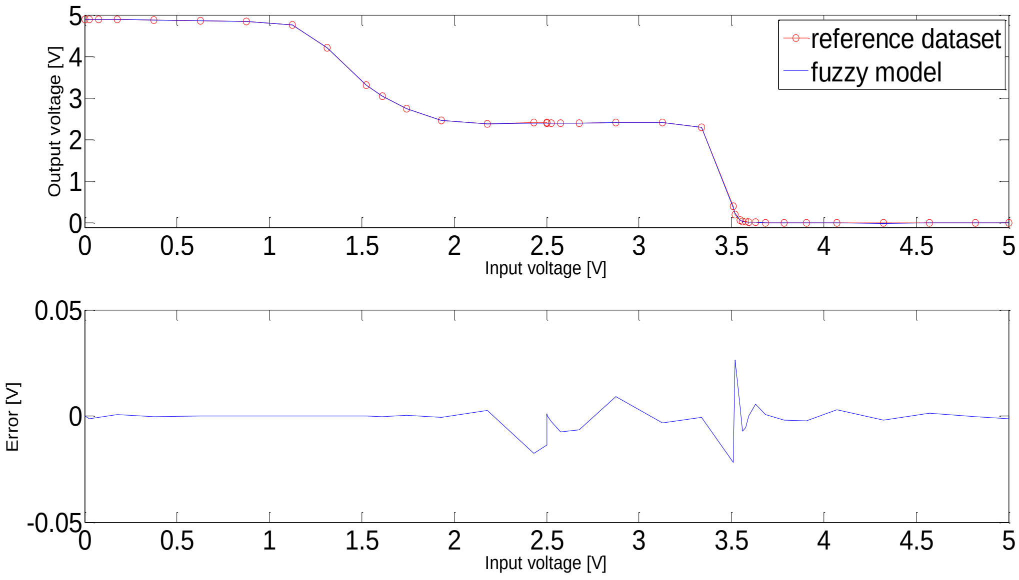

Figure 6. VTC results
a) VTC from the reference dataset and from the fuzzy model
b) point-by-point error between the two VTCs

IV. CONCLUSIONS

This paper presents the development and testing of a fuzzy system that models the voltage transfer characteristic of the simple ternary inverter. The circuit is first implemented and simulated in SPICE environment. Input-output voltage data pairs are collected and then split into two datasets, which will be used for training and checking the fuzzy model. The fuzzy model is developed using specific MATLAB functions. Finally, the model is tested using the checking data set.

The comparison between the voltage transfer characteristic obtained from the reference dataset and the one obtained using the fuzzy model shows the correct functioning of the developed model. The model can be used to replace a circuit level simulation, ensuring very small computational costs. Once the models are developed, they can be used in complex system analyses and design loops, without the need of including an actual circuit simulator.

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