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Evaluation of the Analog Circuits Performances Using Fuzzy Models

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Abstract – The increasing complexity of today electronic circuits requires new accurate and computationally efficient models of circuit functions. Because fuzzy systems are universal aproximators and imply a reduced computation volume, we use them to model the circuits functions. The results obtained for the simple operational transconductance amplifier and for Miller operational transconductance amplifier prove the accuracy and the efficiency of the fuzzy models.

Keywords: circuit performances, fuzzy models, anfis, data sets.

I. INTRODUCTION

Gielen and Rutenbar [1] take into consideration three reasons to develop high level models to describe the electronic circuit behaviours. In a top-down design methodology at higher levels of the design hierarchy, where the detailed lower-level circuit implementations are yet unknown, there is a need for higher-levels models describing the pin-to-pin behavior of the circuits rather than the (yet unknown) internal structural implementation. Second, the verification of integrated mixed-signal systems also requires higher description levels for the analog sections, since such integrated systems are computationally to complex to allow a full simulation of the entire mixed-signal design in practical terms. Third, when providing or using analog IP macrocells in a SoC context, the virtual component has to be accompanied by an executable model that efficiently models pin-to-pin behavior of the virtual component. This model can then be used in system-level design and verification, even without knowing the detailed circuit implementation of the macrocell.

In the optimization based analog design the iterative process needs a large number of circuit performances evaluations and this is the most time-consuming task. A very efficient way to reduce the time spent with these simulations is to build models of circuit functions [2]. Two factors determine the utility of the circuit function model. First, the model should be computationally efficient to construct and evaluate so that substantial computational savings can be achieved. Second the model should be accurate [3].

In order to prevent misguided understanding, we explain for analog circuits the terminology used in this paper:

- **parameters:** quantities which determine the circuit performances (W/L, R, C, etc.);
- **circuit functions:** specific quantities of the circuits (voltage gain, phase margin, unity gain bandwidth, slew rate);
- **performances:** circuit functions values for the known parameters values.

The fuzzy systems are appropriate for modeling because they are universall aproximators [4], [5], [6] and can model any nonlinear, multivariable function.

In this paper we present a strategy to build fuzzy models of circuit functions for analog circuits. We apply this strategy for two circuits: simple operational transconductance amplifier (sota) and Miller operational transconductance amplifier (mota).

The paper is organized as follows. Section II presents the strategy of circuit functions modeling. In Section III the mathematical analysis of the circuits and the parameters and performances used in models is presented. Section IV presents some experimental results for the circuit function models. Finally we conclude our paper in Section V.

II. MODELING STRATEGY

Due to the fact that Takagi-Sugeno fuzzy systems can accurately approximate any complex multivariable functions, we have choused this class of models to construct the fuzzy models for our circuit functions. The structure of the fuzzy models is presented in Fig.1.

According to [5], [7], [2] for building fuzzy models we need a set of numerical data. To obtain accurate models for the analog circuit performances, a large number of data pairs is requested, that should uniformly cover the performance domain and include, as much as possible from his characteristics

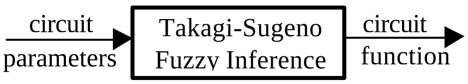

Fig.1. Takagi-Sugeno fuzzy models structure

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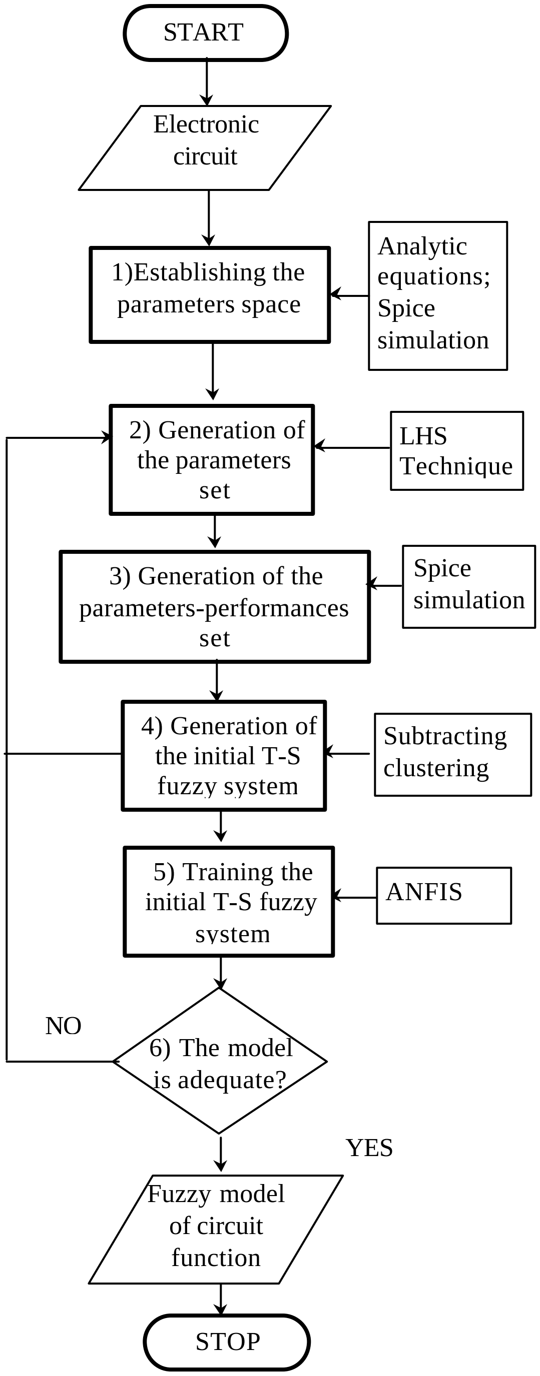

Fig.2 Strategy of circuit functions modeling

Fig.2 presents the strategy of circuit functions modeling. The techniques and methods used in each phase are presented.

1) Establishing the parameters space

The range of the parameters should be choused so that regardless the combination of the parameters values, the circuit always remains in the desired region .

2)Generation of the parameters set

In order to obtain uniformly distributed data pairs we used the Latin Hypercube Sample (LHS) technique [3]. If N is the desired number of data pairs the space of each parameter is divided into N non-overlapping interval of 1/N length. From each interval we obtain a random value and so we will obtain N values for each parameter. Next the N values for one parameter are randomly paired with the N values for another parameter, and so on. In this way we obtain sets of parameter values that will uniformly cover the parameters space.

Note that LHS will provide a more uniform coverage of the parameters space than other experimental design techniques.

3)Generation of the parameters-performances set

The values of circuits function are deduced by Spice simulation. For every parameters pair we run the appropiate simulation profile to compute the circuits function value, and so on for the entire parameters set.

4)Generation of the initial T-S fuzzy system

With the sets of parameters-performances data pairs we will generate and train a Fuzzy Inference System (FIS) as a model for each of our functions. The generation of initial fuzzy model uses a fuzzy subtractive clustering.

5) Training the initial T-S fuzzy system

The initial fuzzy model is than trained with Adaptive-Network-based Fuzzy Inference Systems (anfis), which is the major training routine for Sugeno-type fuzzy inference systems. Anfis uses a hybrid-learning algorithm to identify parameters of Sugeno-type fuzzy inference systems. It applies a combination of the least-squares method and the backpropagation gradient descent method for training FIS membership function parameters to emulate a given training data set. Anfis also performs a model validation using a checking data set, to detect the model overfitting. The fuzzy inference system is trained during a designated number of epochs until overfitting appears or the training error goal is achieved. More details about anfis can be found for example in [7], [8]

6)The model is adequate?

The obtained fuzzy model is then tested. If it is not accurate we could go back to step 2 or 4. If we will return to phase 4 we need to generate another initial fuzzy system with a different number of rules. If the parameters-performances set does not cover enough the functions characteristics (inconsistent data) we will return to step 2 and generate a larger set of data.

III. MATHEMATICAL ANALYSIS OF THE CIRCUITS

A. Simple operational transconductance amplifier

The schematic of the simple operational transconductance amplifier (sota) is presented in Fig3. The design parameters of the circuit are the dimensions of the transistors and the bias current I_b. Happily the parameter numbers will decrease after a simple analysis of the circuit. The input transistors Q_1 and Q_2 must be identical, therefore $(W/L)_1=(W/L)_2$ resulting the first parameter $(W/L)_{12}$. The transistors Q_3 and Q_4 which form the active load must be paired, resulting $(W/L)_3=(W/L)_4$, so our second parameter

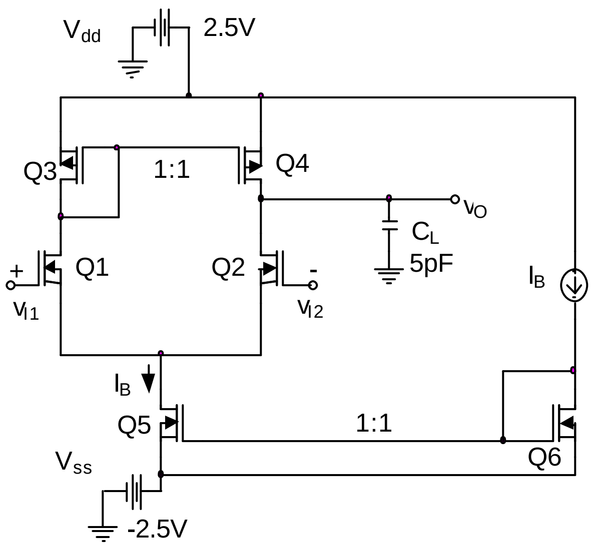

Fig3. Simple operational transconductance amplifier

will be $(W/L)_{34}$. For the current mirror formed by Q_5 and Q_6 we consider the current (I_b) equal trough both transistors so $(W/L)_5=(W/L)_6$. In order to keep an minimal area, we have taken W=L so we obtained our third parameter $(WL)_{56}$ with $W_5=L_5=W_6=L_6$. The fourth and final parameter is I_b.

The range of the parameters should be choused so that regardless the combination of the parameters values, the circuit always operates as an amplifier (all the transistors stay in the active region). In order to assure a high value for the voltage gain, the transistors Q_1 and Q_2 should be biased with a small overdrive voltage $V_{GS12} - V_{Pn} \approx 0.2V$ [10]. To stay in the active region $V_{DS12} > V_{GS12} - V_{Pn} = V_{DS12\ sat}$ and $V_{DS12} > 0,2$ V must be fulfilled. For Q_5 and Q_6 we have $V_{DS56} > V_{GS56} - V_{Pn} = V_{DS56\ sat}$ and taking into consideration their connection $V_{DS56} = V_{GS56} > V_{DS56\ sat}$. For the same reason Q_3 and Q_4 will always stay in the active region. If the transistors work at higher overdrive voltages the matching is better.

It is recommended for Q_3, Q_4 and Q_5, Q_6 to fulfill the relation:

$$\left|V_{GS} - V_p\right| \approx [0.5; 0.7] \qquad (1)$$

The modeling parameters used in simulation are for the 0.25μm technology.

The domains of our parameters are:

$$I_b \in [20; 70]\mu A;$$

$$W12 =: (W/L)_{12} \in [1; 8] \text{ with } L_{12} = 0.5\mu m$$

$$W34 = (W/L)_{34} \in [1; 10] \text{ with } L_{34} = 0.75\mu m;$$

$$W56 = (W/L)_{56} \in [1; 100] \text{ with } (W/L)_{56} = 1.$$

As performances we have choused the important ones:

- Voltage Gain: $Av = \dfrac{V_o}{V_{i1} - V_{i2}}$
- Unity Gain Bandwidth $GBW = Av \cdot B$ (B – passband at 3dB)
- Phase Margin PM
- Common mode rejection ratio: $CMRR = \left|\dfrac{Av}{A_c}\right|$ (A_c – common mode gain)

The simplified mathematical expressions for the circuit performances can be taken from the literature [10],[11],[12] and they are:

$$\mathbf{Av = 2V_E L \sqrt{\frac{1}{I_B} K_n \left(\frac{W}{L}\right)_1}} \qquad (2);$$

$$\mathbf{GBW = \frac{\sqrt{K_n \left(\frac{W}{L}\right)_1 I_B}}{2p(C_{n5} + C_L)}} \qquad (3);$$

$$\mathbf{PM = 90^o - arctan\ \frac{GBW}{f_{nd}} + arctan\ \frac{GBW}{2f_{nd}}} \ (4);$$

$$\mathbf{CMRR = 20lg\left|4V_E \cdot L \cdot V_{EP} \cdot L_5 \frac{1}{I_B} \sqrt{K_n K_P \left(\frac{W}{L}\right)_1 \left(\frac{W}{L}\right)_3}\right|} \ (5);$$

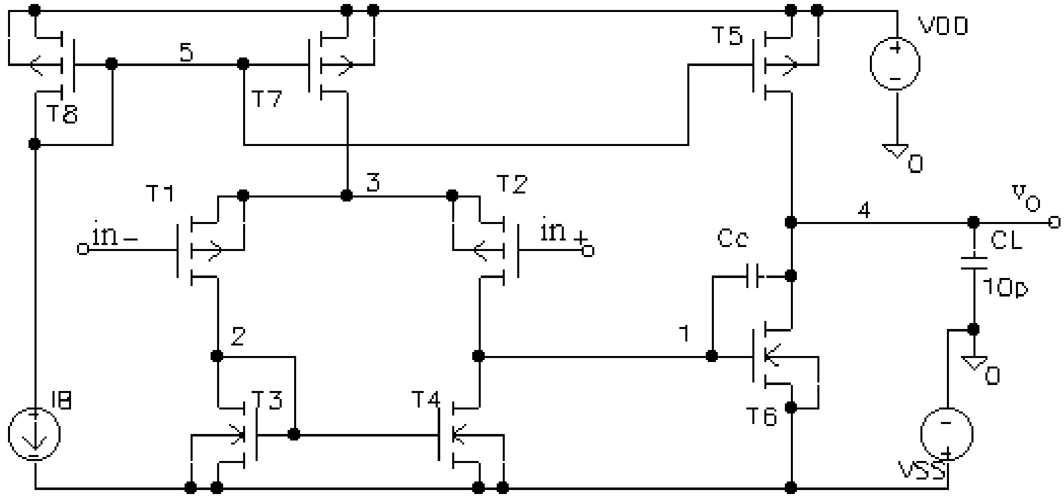

Fig. 4 Miller operational transconductance amplifier

B. Miller operational transconductance amplifier

The schematic for the Miller operational transconductance amplifier (mota) is presented in Fig4.

The design parameters of the circuit are the dimensions of the transistors, the bias current I_b and compensation capacitance C_C.

Not all of the circuit parameters are independent so after the mathematical analysis of the circuit results the four parameters used for modeling the circuit: I_b, (W/L)1, (W/L)6 and C_C

The conditions that all transistors are biased in the active region can be taken from [12], [10].

The domains of the parameters are shown in Table 1.

Table1

Parameter	Parameter domain
I_B [μA]	0.2 – 5
$(W/L)_1$	0.24 – 10
$(W/L)_6$	20 – 500
C_C [pF]	0.2 - 10

As performances we have choused:

- Voltage Gain: $Av = \frac{V_o}{V_{i+} - V_{i-}}$
- Unity Gain Bandwidth $GBW = A_{vo} \cdot B$
- Phase Margin PM
- Slew Rate SR

The simplified mathematical expressions for the circuit performances can be taken also from the literature [10],[13],[14],[15] and they are:

$$Av = \frac{a_2}{a_3} \frac{\sqrt{\left(\frac{W}{L}\right)_1} \sqrt{\left(\frac{W}{L}\right)_6} \sqrt{\left(\frac{W}{L}\right)_7}}{I_b \sqrt{\left(\frac{W}{L}\right)_5}} \qquad (6)$$

$$GBW = a_1 \frac{\sqrt{I_b} \sqrt{\left(\frac{W}{L}\right)_1}}{C_C} \qquad (7)$$

$$PM = 90 - \mathrm{arctg}(a_4) \frac{\sqrt{\left(\frac{W}{L}\right)_1} \sqrt{\left(\frac{W}{L}\right)_7}}{\sqrt{\left(\frac{W}{L}\right)_6} \sqrt{\left(\frac{W}{L}\right)_5}} \qquad (8)$$

$$SR = \min\left(\frac{I_B}{Cc}, \frac{9I_B}{C_L}\right) \qquad (9)$$

IV. EXPERIMENTAL RESULTS

A. Simple operational transconductance amplifier

We built our fuzzy models for each circuit function with a set of 850 data pairs (700 training pairs and 150 checking pairs) for different number of rules. We used a small number of rules (3 rules), a medium number (6 rules) and a large number (10 rules).

For testing the accuracy of the fuzzy models, we evaluated the models with two sets of set of data pairs. One set of data that was not included in the training and verification sets (**test data**) and a set of data pairs included in the training set (**verification data**). Ten data pairs compose each of these two sets of verification data. In order to evaluate the models quality we used the relative error calculated between the performances values from the data sets and the functions values obtained with the fuzzy models.

The relative errors for the voltage gain (Av) are presented in Fig5. It can be easily observed that for a number of **medium rules (6 rules)** the relative errors obtained are the smallest. Therefore we built our circuit functions models with a medium number of fuzzy rules

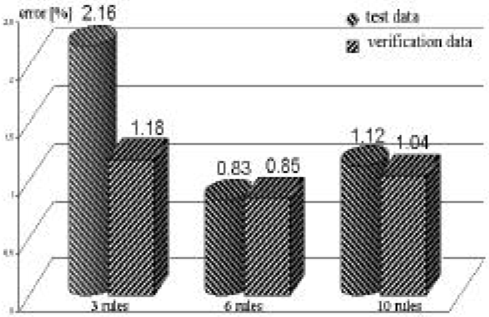

Figure5. Relative errors for the voltage gain

The surface of the Av fuzzy model is presented in Fig6.

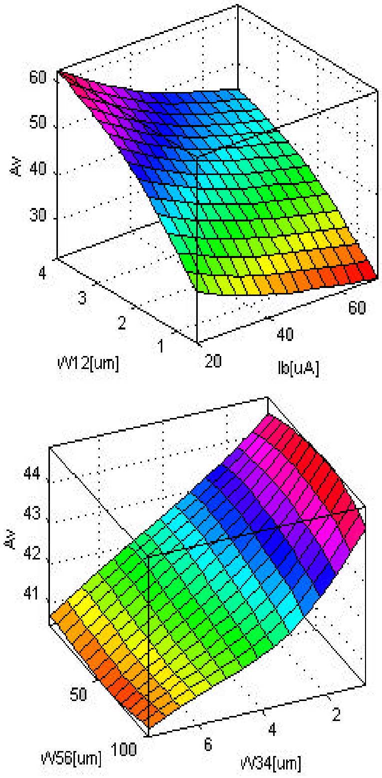

Fig6The surface of the Av fuzzy model

In Fig7a, b we present the matching between the function values obtained with the fuzzy model and with the test and verification sets, for Av

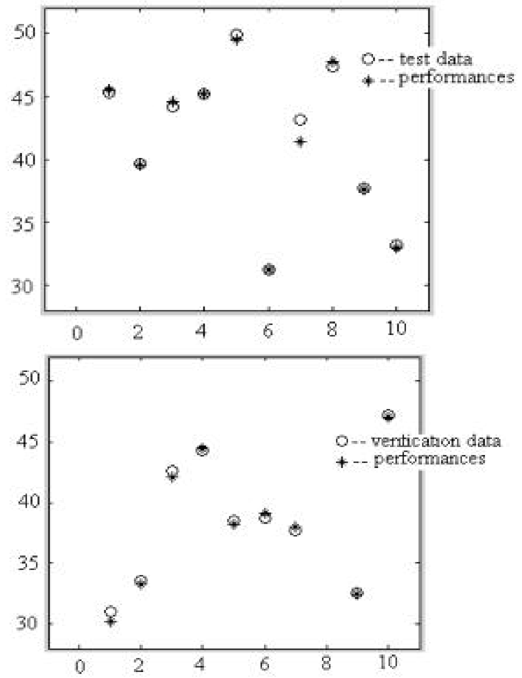

Fig. 7 The function values obtained with the fuzzy model and with the test and verification sets

In Table 2 we present the mean, the minimum and maximum values of the relative error for the circuit function models.

Table2

Circuit function	Data set	Relative error [%]		
		Mean	Minimum	Maximum
Av	Test data	0.83	0.03	1.01
	Verification data	0.85	0.35	2.57
GBW	Test data	3.07	0.99	8.53
	Verification data	1.81	0.30	5.20
PM	Test data	0.03	0	0.10
	Verification data	0.02	0	0.11
CMRR	Test data	3.04	0.30	8.74
	Verification data	4.67	2.80	9.24

In Table3 we show the necessary CPU time to compute the performance values with the fuzzy models and with the Pspice simulator (system configuration: DURON 950MHZ and 256MRAM).

Table3

Computed with	CPU Time [ms]
Fuzzy models	25
Pspice	850

The experimental results for sota show that the best fuzzy model for avo, gbw, pm and cmrr is the fuzzy system with 6 rules (medium number) and 850 data pairs

B. Miller operational transconductance amplifier

The structure of the fuzzy systems built for mota is analogue with the systems obtained for sota and the best fuzzy systems are:

- For Av 9 rules
- For GBW 10 rules
- For PM 11 rules
- For SR 7 rules

In Table4 the mota circuit functions is presented

Table 4

Circuit function	**Mean relative error [%]**	
	Training	**Verification**
Av	22,84	16,68
GBW	19,25	22,81
PM	6,23	5,83
SR	14,05	12,45

The values presented in Table 4 are relative big. There are two reason for this: the data set was strongly affected by noise, the range of circuits function values are very large (for example for GBW the functions values being in the range of 320-7423KHz) and to reduce these relative errors we should generate a large data set rebuild the fuzzy models.

In Fig8 we present the matching between the function values obtain with the fuzzy model and with Pspice simulation for GBW and SR.

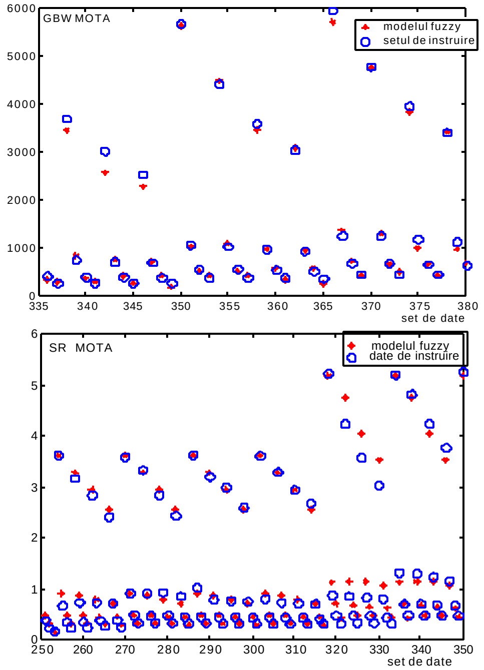

Fig8. Matching between fuzzy model values and values obtained with Pspice for GBW and SR

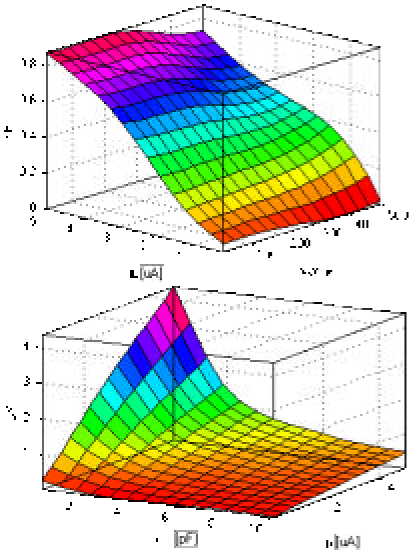

Fig9. The surface of the sr fuzzy model

The surface of the sr fuzzy model is presented in Fig9

V. CONCLUSIONS

Fuzzy models approximate very well the circuit functions, the relative error in the test data set being in the range of (0.02-4.67%) for sota. The relative error is bigger for the circuit functions with a larger performances domain and is very small for a narrow performances domain. For the common mode rejection ratio we had the biggest errors, the domain of the performances being in the range of (2512-1654235) and for the phase margin we had the smallest errors, the performances domain being in the range of (90.82-92.13). If the performances domains are large we need a bigger number of parameters-performances pairs to obtain greater accuracy.

If we have a small number of fuzzy rules the system cannot approximate the function very well and if we have a big number of rules, the number of model coefficients, which need to be tuned, is very big and will need a greater number of data pairs. Therefore we have to find an optimum number of rules to build the circuit functions models.

Evaluation of the circuit performances with fuzzy models requires a much smaller time than the evaluation by Pspice simulation.

All of the experimental results obtained for the simple operational transconductance amplifier and for Miller operational transconductance amplifier prove the accuracy and the efficiency of the fuzzy models.

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