Automated Observability Investigation of Analog Electronic Circuits using SPICE

Elissaveta Dimitrova Gadjeva, Dimitar Yordanov Shikalanov and Anton Georgiev Atanasov

Abstract – **In the present paper, a computer-aided approach to fault observability investigation of linear analog circuits is developed. The method is based on sensitivity investigation of the test characteristics in the frequency domain. The test frequencies are selected maximizing the sensitivity of the magnitude of the test characteristics. Applying post-processing of the simulation results using macrodefinitions in the graphical analyzer *Probe*, a fault observability investigation of the circuit is performed. A number of sensitivity measures are defined in *Probe* for observability investigation of multiple faults using pre-defined macrodefinitions. The sensitivity of *S*-parameters is obtained in order to investigate the fault observability at RF.**

Keywords – **Analog circuit diagnosis, Sensitivity, Fault observability, SPICE simulation**

I. INTRODUCTION

The development of testability-oriented design techniques for mixed-signal/RF integrated circuits requires study of testability and sensitizing the RF test paths for the defects in the circuits, investigation of detectability of faults, masking effects, influence of circuit tolerances. This allows to enhance the fault coverage of the tests. In order to achieve high performance, efficient test and diagnosis procedures are needed. Due to the complexity of testing at higher frequencies, the testing of RF analog circuits requires performing a quick and efficient test with a limited number of test vectors.

In [1] a parametric fault diagnosis approach to analog/RF circuits based on a Bayesian framework is proposed. Using sensitivity investigation, the optimal test set is selected to distinguish the faults and to increase the diagnostic resolution. In [2] a method is developed for improving fault detection in high frequency circuits based on sensitivity analysis and *S*-parameter measurements. The test frequencies are selected maximizing the sensitivity of the magnitude and phase of the *S*-parameters. The symbolic methods are ineffective for sensitivity determination of large circuits. The numerical approaches to sensitivity investigation such as sensitivity model method [3] and adjoint circuit method, lead to faster simulation and can be implemented in standard circuit simulators. The influence of the faults on the output characteristics is investigated in [4]. The concepts fault masking, fault dominance, fault equivalence and fault isolation are defined. A masking exists if $S_{x_i}^{y_j} = -S_{x_k}^{y_j}$ for each frequency. Fault dominance exists if $S_{x_i}^{y_j} \square\ S_{x_k}^{y_j}$ for each frequency, and the faults are equivalent if $S_{x_i}^{y_j} = S_{x_k}^{y_j}$ for each frequency.

Based on sensitivity analysis, test nodes and test frequencies selection is performed for every category of faults (single, double, multiple).

In the present paper, a computer-aided approach is developed to fault observability investigation of linear analog circuits. The method is based on sensitivity investigation of the test characteristics. The sensitivities of the *S*-parameters are obtained based on sensitivity model approach. It is implemented in the *Cadence PSpice* simulator. Parameterized sensitivity *PSpice* macromodels are built in order to calculate the sensitivity characteristics in the frequency domain.

Applying post-processing of the simulation results using macrodefinitions in the graphical analyzer *Probe*, a fault observability investigation of the circuit is performed. Sensitivity measures are defined in *Probe* for observability investigation of multiple faults using pre-defined macrodefinitions. The fault masking, fault dominance and fault equivalence can be investigated. The frequency ranges, corresponding to maximal sensitivity measures, are automatically obtained for the multiple fault isolation. Examples are given illustrating the possibilities and the applicability of the proposed approach.

II. SENSITIVITY MODEL

The sensitivity characterizes the influence of the circuit parameter deviations on the circuit characteristics:

$$S_{Y_i}^{V_{out}} = \frac{\partial V_{out}}{\partial Y_i} \cdot \frac{Y_i}{V_{out}}\,, \tag{1}$$

where V_{out} is the output test voltage and Y_i is the admittance of the element. The sensitivity model approach [3] is used to calculate the sensitivity coefficients of the output characteristics in the frequency domain. According to this method, in order to obtain the derivative of the output voltage V_{out} in respect to the admittance Y_i in the circuit, an analysis of the original circuit N is performed and the resulting voltage V_{Yi} is used as a control voltage for the sensitivity model N_d, which is a copy of the original circuit N. A voltage controlled current source is connected in parallel with the element Y_{id} in circuit N_d with controlling coefficient Y_c = 1S. The output voltage of the circuit N_d is equal to the derivative $\partial V_{out} / \partial Y_i$.

E. Gadjeva is with the Department of Electronics and Electronic Technologies, Faculty of Electronic Engineering and Technologies, Technical University - Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: egadjeva@tu-sofia.bg

D. Shikalanov is with the Department of Informatics, New Bulgarian University, Montevideo 21 Str., 1635 Sofia, Bulgaria, e-mail: dys@nbu.bg

A. Atanasov is with XPEQT Ltd., 2, Samokovsko Shosse, 1138 Sofia, Bulgaria, e-mail:antonatan@abv.bg

In order to obtain the sensitivity using standard circuit simulators such as *PSpice*, the controlling coefficient Y_c in the computer model is multiplied by Y_i. A parametric analysis of the original circuit N and of the sensitivity model N_d is simultaneously performed.

As a result, the output voltage $V_{out,d}$ of the circuit N_d is obtained:

$$V_{out,d} = \frac{\partial V_{out}}{\partial Y_i} \cdot Y_i \,. \tag{2}$$

Finally, the sensitivity $S_{Y_i}^{V_{out}}$ is calculated in the graphical analyzer *Probe* dividing $V_{out,d}$ by V_{out} :

$$S_{Y_i}^{V_{out}} = \frac{\partial V_{out,d}}{V_{out}} \,. \tag{3}$$

The computer realization of the sensitivity models is performed in [5] for resistor and capacitor elements. The sensitivity model of the inductor element using hierarchical block is shown in Fig. 1. In order to analyze simultaneously the circuits N and N_d, the equivalent circuit contains the element L_1 from the original circuit N and the element L_{1A} from the sensitivity model N_d. The VCCS $G1$ is added in parallel with L_{1A} in the sensitivity model. The circuit connections are represented using busses. The node 1 has a bus name 1[1..2] and represents node 11 of the circuit N and node 12 in the circuit N_d (Fig. 1c). The attributes of the block are shown in Fig. 1b. The *ID* number is assigned to the element. In order to obtain simultaneously the sensitivities for a group of elements in the graphical analyzer *Probe*, a parametric sweep is used. A parameter *par* is defined with linear variation from 1 to n with increment 1. When the current value of the parameter *par* is equal to the *ID* number of a given element, the controlling coefficient G_{gen} of its *VCCS* is equal to the admittance Y_L=1/(sL) and the sensitivity with respect to this element is calculated, otherwise G_{gen}=0. This is accomplished by the **IF-THEN-ELSE** statement, included in the expression for G1 (Fig. 1c). The XFORM attribute is equal to the admittance 1/(s*@val). The definition in the EXPRESSION field has the form:

```
V(%IN+, %IN-)*{if(abs(@par-@IDN)<0.1,1,0)}
```

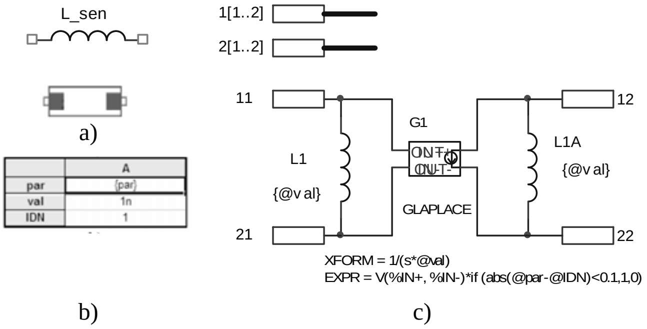

Fig. 1. Computer realization of the sensitivity model of inductor element using hierarchical block

A number of fault observability measures can be defined based on sensitivity calculation [4, 5]: M_1^n, M_2^n and M_3^n. The measure M_1^n is defined as a sum of modules of the sensitivities with respect to the element parameters $Y_1, Y_2, \ldots, Y_n$.

$$M_1^n = \sum_{i=1}^{n} \left| S_{Y_i}^{V_{out}} \right| . \tag{4}$$

N-fold fault of the defined group of elements can be detected in the frequency ranges, where the measure M_1^n has a maximum value.

In order to avoid fault dominance, the measure M_2^n can be used in the form.

$$M_2^n = M_1^n \prod_{i=1}^{n} \left| S_{Y_i}^{V_{out}} \right| . \tag{5}$$

Multiplying the measure M_1^n by the product of sensitivities, the frequency ranges corresponding to low sensitivity values for some of the elements, are skipped and the fault dominance is avoided. N-fold fault of the defined group of elements can be detected in the frequency ranges, where the measure M_2^n has a maximum value.

A variant of the measure M_1^n is the measure M_3^n. It is defined in the following way:

$$M_3^n = M_1^n E \,, \tag{6}$$

where E is enable function:

$$E = \prod_{i=1}^{n} E_i \,, \tag{7}$$

$$E_i = \begin{cases} 1 \text{ if } \left| S_{Y_i}^{V_{out}} \right| \geq \varepsilon M_1^n \\ 0 \text{ if } \left| S_{Y_i}^{V_{out}} \right| < \varepsilon M_1^n \end{cases} , \tag{8}$$

where ε is a threshold parameter, defining the minimal allowed ratio between the individual sensitivity and the measure M_1^n. It is needed to avoid dominance. If E = 0, a fault dominance exists and the value of the measure M_3^n in these frequency ranges is set to zero.

The sensitivities $S_{Y_i}^{V_{out}}$ and the measures: M_1^n, M_2^n and M_3^n are calculated in the graphical analyzer *Probe*.

For example, the measure M_1^1 for testing the circuit parameter with *ID* number p has the form:

```
SEN(p)=M(V(OUT2)@p/V(OUT1)@p)
```

where V(OUT1) is the output voltage of the circuit N and V(OUT2) is the output voltage of the circuit N_d.

The measures M_1^2, M_2^2 and M_3^2 for testing a double fault in circuit elements with *ID* numbers p_1 and p_2, have the form:

```
*eqn (4)
MS1_2(p1,p2)=SEN(p1)+SEN(p2)
*eqn. (5)
MS2_2(p1,p2) = (SEN(p1)+SEN(p2))*SEN(p1)*SEN(p2)
*eqn. (7)
E_2(p1,p2) = 0.5*(sgn(SEN(p1)/MS2_2(p1,p2))-eps)+1)*
0.5*(sgn(SEN(p2)/ MS2_2(p1,p2))-eps)+1)
*eqn. (6)
MS3_2(p1,p2)= MS2_2(p1,p2) * E_2(p1,p2)
```

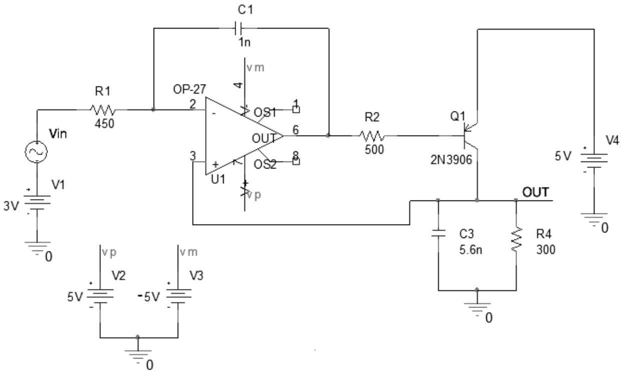

Fig. 2. Example circuit for sensitivity investigation

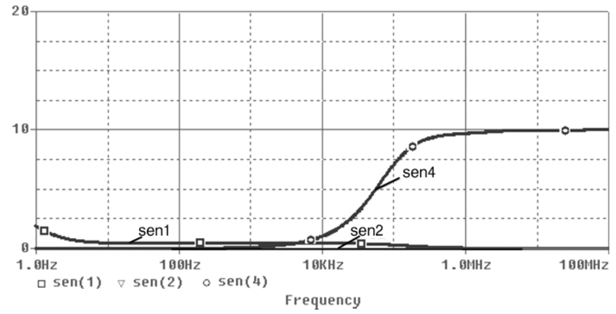

Fig. 3. Sensitivity coefficients $\left|S_{R_1}^{V_{out}}\right|$, $\left|S_{C_1}^{V_{out}}\right|$ and $\left|S_{C_3}^{V_{out}}\right|$

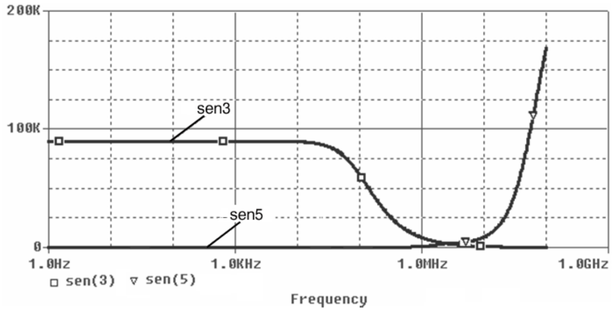

Fig. 4. Sensitivity coefficients $\left|S_{R_4}^{V_{out}}\right|$ and $\left|S_{R_5}^{V_{out}}\right|$

As an example, the results of the sensitivity investigation of the circuit of the current sink [6] are presented in Fig. 2. The sensitivities to the parameters of the resistor R_1 (SEN(1)), capacitor C_1 (SEN(2)) and capacitor C_3 (SEN(4)) are presented in Fig. 3. The sensitivities to the parameters of the resistor R_4 (SEN(3)) and resistor R_5 (SEN(5)) are presented in Fig. 4.

The measure M_1^2 for testing the components C_1 and R_4 MS1_2(2,3) is presented in Fig. 5. The measure M_2^2 for testing the same components MS2_2(2,3) is presented in Fig. 6. It is seen that the measure M_2^2 takes into account the total sensitivity and the influence of the individual sensitivities of the tested elements in the group to avoid fault dominance.

Corresponding macrodefinitions are created for multiple fault observability using the measures M_1^n, M_2^n and M_3^n. The measure $M_1^2\left(C_1,R_4\right)$ defined as a sum of sensitivities for two components $\left(C_1,R_4\right)$ is presented in Fig. 5.

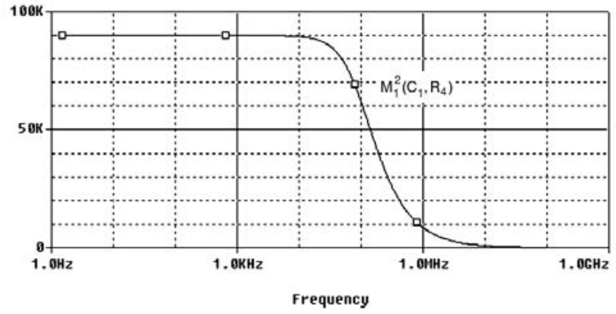

Fig. 5. The measure $M_1^2\left(C_1,R_4\right)$ for testing the components C_1 and R_4

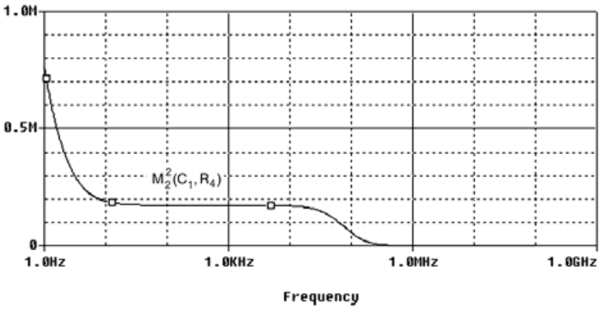

Fig. 6. The measure $M_2^2\left(C_1,R_4\right)$ for testing the components C_1 and R_4

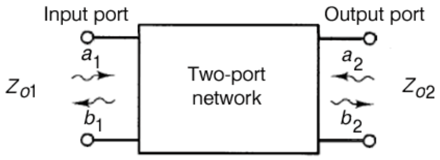

Fig. 7. Two-port *S*-parameters

The measure $M_2^2\left(C_1,R_4\right)$ taking into account the influence of the sensitivity value for each of the components, is presented in Fig. 6.

The approach is extended for the case of sensitivity determination of two-port *S*-parameters (Fig. 7). This allows to investigate the fault observability of RF circuits using general purpose analysis programs.

The approach developed in [7] is used for the *S*-parameter determination in the *PSpice* environment using parametric analysis (Fig. 8). Macrodefinitions in *Probe* are used for the S-parameter determination defined by the following expressions:

$$\begin{aligned} &S_{11}=\frac{2\dot{V}_1}{\dot{V}_{g1}}-1;\ S_{21}=\frac{\dot{V}_2}{\dot{V}_{g1}} \quad \text{for } V_{g2}=0, \\ &S_{12}=\frac{\dot{V}_1}{\dot{V}_{g2}};\ S_{22}=\frac{2\dot{V}_2}{\dot{V}_{g2}}-1 \quad \text{for } V_{g1}=0. \end{aligned} \tag{9}$$

The corresponding macrodefinitions have the form:

S11=2*V(1)@1-1
S12=V(1)@2 (10)
S21 = V(2)@1
S22=2*V(2)@2-1

where @1 is used for the data of the first simulation (*par* = 0) and @2 is used for the data of the second simulation (*par* = 1).

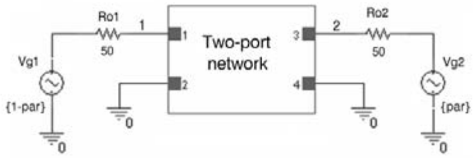

Fig. 8. *S*-parameter determination using *PSpice*

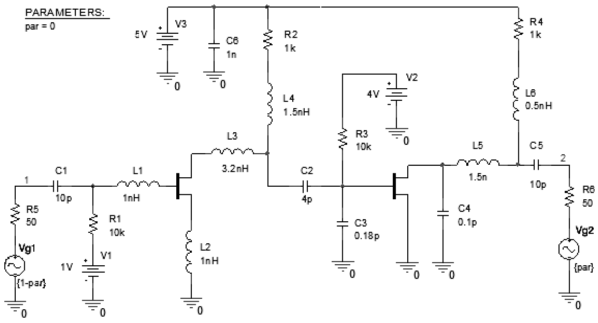

Fig. 9. Schematic of the low noise amplifier

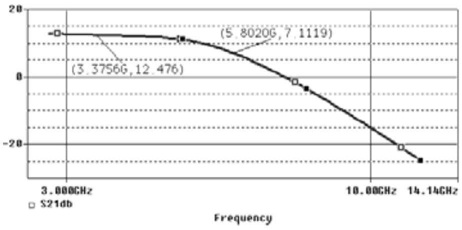

Fig. 10. Module of S_{21}

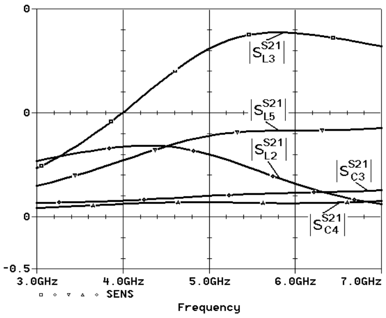

Fig. 11. The modules of sensitivities of S_{21} with respect to the elements L_2, L_3, L_5, C_3 and C_4

The low-noise amplifier [8] is used to illustrate the fault observability of electronic circuits at RF based on sensitivity analysis ot the two-port *S*-parameters. AC sweep is performed in the frequency range (3GHz – 7GHz). The macrodefinitions (10) are used for the *S*-parameter calculation in the graphical analyzer *Probe*. The result for the module of S_{21} in dB is shown in Fig. 10. The modules of the sensitivities of S_{21} with respect to the elements L_2, L_3, L_5, C_3 and C_4 are presented in Fig. 11. The frequencies, which ensure maximal observability of single faults, correspond to the maximum values of these sensitivities. The measures $M_1^2(L_2, L_5)$ and $M_2^2(L_2, L_5)$ are presented in Fig. 12. The frequencies, which ensure maximal observability of double faults, correspond to the maximum values of the defined measures. For the considered case, similar frequency values are obtained for the maximal fault observation (4.82GHz applying the measure $M_1^2(L_2, L_5)$ and 4.87GHz applying the measure $M_2^2(L_2, L_5)$).

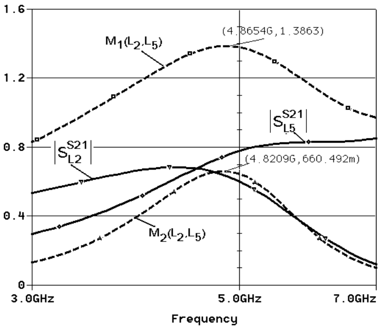

Fig. 12. Measures $M_1^2(L_2, L_5)$ and $M_2^2(L_2, L_5)$

III. CONCLUSION

A computer-aided approach has been developed to fault observability investigation of linear analog circuits. The method is based on sensitivity investigation of the test characteristics in the frequency domain. A number of sensitivity measures are defined in *Probe* for observability investigation of multiple faults using pre-defined macrodefinitions. The sensitivity of *S*-parameters is obtained in order to investigate the existence of fault masking, fault dominance and fault equivalence at RF.

IV. ACKNOWLEDGEMENT

The investigations are supported by UNIK project DUNK-01/03-12.2009.

REFERENCES

[1] Fang Liu, P. Nikolov, S. Ozev. *Parametric fault diagnosis for analog circuits using a Bayesian framework*, Proceedings of 24th IEEE VLSI Test Symposium, 30 April-4 May 2006, ISBN: 0-7695-2514-8

[2] I. Sylla, M. Slamani. *Improving Design and Fault Detection in Linear and Nonlinear High Frequency Circuits by Performing a Sensitivity Based Analysis*, Analog Integrated Circuits and Signal Processing, Kluwer Academic Publishers, v. 27, pp. 249–260, 2001.

[3] J. Vlach, K. Singhal. *Computer methods for circuit analysis and design*, Kluwer, 1983.

[4] M. Slamani, B. Kaminska. *Fault observability analysis of analog integrated circuits in frequency domain*, IEEE Transactions on Circuits and Systems, February 1996, pp. 134–139.

[5] E. Dimitrova, E. Gadjeva, D. Shikalanov, V. Valchev. *Diagnosability Investigation of Linear Analog Circuits Using Parameterized Sensitivity SPICE macromodels*, Advanced Aspects of Theoretical Electrical Engineering, Sozopol'2009, 20-23 Sept. 2009, Sozopol, Bulgaria.

[6] T. Green. *Operational Amplifier Stability - Part 5: Real-World Design of a Single supply buffer circuit*, Burr-Brown, 2010,http://www.en-genius.net/site/zones/acquisitionZONE/technical_notes/acqt_092407

[7] E. Gadjeva, T. Koyoumdjiev, S. Farchy, M. Hristov, A. Popov. *Computer modeling and simulation of electronic and electrical circuits using Cadence PSpice*, Sofia, Meridian 22, 2000.

[8] M. Golio. *The RF and Microwave Handbook*, ,Boca Raton: CRC Press LLC,2001