Automated Observability Investigation of Analog Electronic Circuits using SPICE

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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 \( S_{ik}^{\text{out}} = -S_{ik}^{y} \) for each frequency. Fault dominance exists if \( S_{ik}^{y} \cap S_{ik}^{\text{out}} \) for each frequency, and the faults are equivalent if \( S_{ik}^{y} = S_{ik}^{\text{out}} \) 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:

\[
S_{ik}^{\text{out}} = \frac{\partial V_{\text{out}}}{\partial Y_{i}} \frac{Y_{i}}{V_{\text{out}}},
\]

where \( V_{\text{out}} \) 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 \( V_{\text{out}} \) in respect to the admittance \( Y_{i} \) in the circuit, an analysis of the original circuit \( N_{o} \) is performed and the resulting voltage \( V_{Y_{i}} \) is used as a control voltage for the sensitivity model \( N_{d} \), which is a copy of the original circuit \( N_{o} \). A voltage controlled current source is connected in parallel with the element \( Y_{d} \) in circuit \( N_{d} \) with controlling coefficient \( Y_{c} = 1.5 \). The output voltage of the circuit \( N_{d} \) is equal to the derivative \( \frac{\partial V_{\text{out}}}{\partial Y_{i}} \).
In order to obtain the sensitivity using standard circuit simulators such as PSpice, the controlling coefficient $Y_i$ 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:

$$V_{out,d} = \frac{\partial V_{out}}{\partial Y_i} \cdot Y_i. \quad (2)$$

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

$$S_{V_{out}}^{V_{out,d}} = \frac{\partial V_{out,d}}{V_{out}}. \quad (3)$$

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 $L_{1,d}$ from the sensitivity model $N_d$. The VCCS G1 is added in parallel with $L_{1,d}$ 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 $Y_i=1/(sL)$ 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*abs(val)). The definition in the EXPRESSION field has the form:

$$V(\%IN+,\%IN-)*if(abs(\%par-\%IDN)<0.1,1,0)$$

![Diagram](image)

**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]: $M_1^*$, $M_2^*$ and $M_3^*$. The measure $M_1^*$ is defined as a sum of modules of the sensitivities with respect to the element parameters $Y_1, Y_2, \ldots, Y_n$.

$$M_1^* = \sum_{i=1}^{n}|S_i^{V_{out}}|. \quad (4)$$

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

In order to avoid fault dominance, the measure $M_2^*$ can be used in the form:

$$M_2^* = M_1^* \prod_{i=1}^{n} |S_i^{V_{out}}|. \quad (5)$$

Multiplying the measure $M_1^*$ 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 $M_2^*$ has a maximum value.

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

$$M_3^* = M_1^* \cdot E, \quad (6)$$

where $E$ is enable function:

$$E = \prod_{i=1}^{n} E_i, \quad (7)$$

$$E_i = \begin{cases} 1 & \text{if } |S_i^{V_{out}}| \geq \varepsilon M_1^*, \\ 0 & \text{if } |S_i^{V_{out}}| < \varepsilon M_1^*. \end{cases} \quad (8)$$

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

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

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

$$\text{SEN}(p)=\text{M}(\text{V}(\text{OUT2})@p)\text{V}(@\text{V}(\text{OUT1})@p)$$

where $\text{V}(\text{OUT1})$ is the output voltage of the circuit $N$ and $\text{V}(\text{OUT2})$ is the output voltage of the circuit $N_e$.

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

$$\text{MS1}_2(p_1,p_2)=\text{SEN}(p_1)+\text{SEN}(p_2) \quad \text{*eqn. (4)}$$

$$\text{MS2}_2(p_1,p_2)=(\text{SEN}(p_1)+\text{SEN}(p_2))\cdot\text{SEN}(p_1)\cdot\text{SEN}(p_2) \quad \text{*eqn. (5)}$$

$$\text{E}_2(p_1,p_2)=0.5*(\text{sgn}(\text{SEN}(\text{p}_1)/\text{MS2}_2(p_1,p_2))-\text{eps})+1)*0.5*(\text{sgn}(\text{SEN}(\text{p}_2)/\text{MS2}_2(p_1,p_2))-\text{eps})+1 \quad \text{*eqn. (6)}$$

$$\text{MS3}_2(p_1,p_2)=\text{MS2}_2(p_1,p_2)\cdot \text{E}_2(p_1,p_2) \quad \text{*eqn. (7)}$$

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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 \( M_1^1 \), \( M_2^1 \) and \( M_3^1 \). The measure \( M_1^1 (C_i, R_j) \) defined as a sum of sensitivities for two components \( (C_i, R_j) \) is presented in Fig. 5.
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 of 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 $M_{11}^2(L_2, L_3)$ and $M_{11}^3(L_2, L_3)$ 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 $M_{11}^2(L_2, L_3)$ and 4.87GHz applying the measure $M_{11}^3(L_2, L_3)$).

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

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REFERENCES