Test variables selection and multiple parametric faults detection in nonlinear analog circuits

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Abstract - ***A method to select diagnosis variables or test variables for analog circuit testing and to diagnose multiple soft faults in non linear analog circuits using multiple frequency measurements is proposed in this paper. Circuit parameters or the test variables are derived by simulating the circuit under test (CUT) using Modified nodal analysis (MNA) method and are selected based on test vectors. Test vectors associated with each component of CUT are generated with the knowledge of circuit topology and the component values. Testing is performed at multiple frequency measurements to solve the component tolerance challenge in analog circuit testing. The results obtained from simulation of benchmark circuits show the effectiveness of the proposed approach***

Key Words: *analog circuit – fault diagnosis – test vector –tolerance –test variable – multiple frequency-modified nodal analysis*

1. INTRODUCTION

Analog circuit testing is an important research topic because of non availability of standard procedures or models. The research challenges such as component tolerance, diagnosis variables or test variables, number of diagnosis variables, suitable test frequencies and test nodes selection in analog circuit testing limit the development of standardized approaches for testing. Analog circuit faults are classified as hard faults or catastrophic faults and soft faults or parametric faults. Parametric faults are defined as the variation in component values and hard faults are open or short circuits. Most of the research proposals are for parametric faults detection because parametric faults lead to system performance degradation and are hard to detect. A method based on thresholding approach to detect multiple parametric faults in linear analog circuits is proposed by G.Puvaneswari in [1]. Jian Sun proposed principal component analysis (PCA) and particle swarm optimization (PSO) support vector machine (SVM) based analog circuit fault diagnosis method [2]. To reduce the fault feature dimension principal component analysis and data normalization is used as preprocessing and support vector machine method is used to diagnosis, and particle swarm optimization is used to optimize the penalty parameters and the kernel parameters of SVM, that improve the recognition rate of the fault diagnosis. A slope fault model based fault dictionary approach is proposed by Yang in [3] to select test points and diagnose parametric and hard faults. In [4], Long B introduced a near-optimal feature vector selection method based on Mahalanobis distance for diagnosis of analog circuits using the least squares SVM (LS-SVM). In [1], G.Puaneswari proposed a test vector based multiple fault diagnosis of linear analog circuits. Multiple faults are identified based on the threshold estimated from the fault variables derived for the components of the CUT. A component is said to be faulty if the fault variable is less than the threshold. This paper uses the threshold approach proposed in [1] to detect multiple parametric faults in nonlinear analog circuits and to solve tolerance issue in testing; testing is done at multiple frequency measurements. Test variables selection is done through the test vector values.

This paper is organized as follows. Section 2 explains the mathematical background of the paper. Section 3 describes the test flow and section 4 illustrates the proposed approach with simulation results on bench mark circuits and discuss the results. Section 5 concludes.

2. MATHEMATICAL BACKGROUND

Testing of analog circuits begins with the simulation of the CUT and deriving the diagnosis variables such as node voltages and branch currents. The simulation of an electronic circuit involves formulation of the circuit equation and solving it for the unknowns. To simulate the CUT, Modified Nodal Analysis (MNA) is used as explained by C.-W.Ho & Jiri Vilach in [5] & [6]. MNA for linear systems results in the system equation of the form

$$AX = Z \tag{1}$$

where A is the coefficient matrix, X is the unknown vector consists of circuit variables (node voltages and few branch currents) and Z is the excitation matrix. The circuit coefficient matrix is formed by the sub matrices,

$$A = \begin{bmatrix} G & B \\ C & D \end{bmatrix} \tag{2}$$

G is the conductance of the components in the CUT and the values of G are determined by the interconnections of the circuit components. B and C matrices consist of 0, 1,-1 and the values are based on the interconnections of the voltage sources. The D matrix is developed with zeros for independent sources and has nonzero values for dependent sources. X is the unknown vector consists of circuit variables (node voltages and few branch currents which are useful for testing and Z is the excitation matrix. The right hand side matrix (Z) consists of the values of independent current and voltage sources. The unknown vector is found by matrix inverse operation.

$$X = \begin{bmatrix} V_n \\ I_v \end{bmatrix} \tag{3}$$

$$Z = \begin{bmatrix} I \\ V \end{bmatrix} \tag{4}$$

In case of non linear circuits, the nonlinear devices are replaced by its linearized complete small signal model as explained by Adel S. Sedra in [8]. Non linear device terminal currents are introduced as unknown currents in addition to other circuit parameters. As the non linear devices are dependent sources D matrix consists of values corresponding to the device parameters. Faults in the CUT are simulated using Fault Rubber Stamp (FRS) as explained by Jose A. Soares Augusto in [7]. FRS is based on the MNA stamp of the components of a CUT. The MNA stamp of a component C_n connected in between the nodes j and j' (V_j , V_j'- respective node voltages) ,in the coefficient matrix is,

$$\begin{array}{c c} & \begin{array}{cc} V_j & V_j' \end{array} \\ \begin{array}{c} j \\ j' \end{array} & \begin{bmatrix} +C_n & -C_n \\ -C_n & +C_n \end{bmatrix} \end{array} \tag{5}$$

If this component is assumed to be faulty, its value changes from C_n to $C_n \pm \Delta$. This deviation causes the current through that faulty component to deviate from its nominal value. This current deviation called fault variable (ϕ) is introduced in the faulty circuit unknown matrix as an unknown branch current. To indicate the current deviation through the faulty component, the faulty component is represented as a parallel combination of its nominal value and the deviation (Δ) (fig.1). V_j and V_j' are the node voltages at the nodes j and j' respectively. i_f is the current deviation through the faulty component.

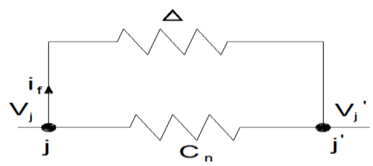

Fig-1: Faulty Component representation

The fault rubber stamp for the component C_n is,

$$\begin{array}{c c} & \begin{array}{cccc} V_j & V_j' & & i_f \end{array} \\ \begin{array}{c} j \\ j' \\ \\ f \end{array} & \left[\begin{array}{ccc|c} +C_n & -C_n & \vdots & 1 \\ -C_n & +C_n & \vdots & -1 \\ \cdots & \cdots & \cdots & \cdots \\ \hline 1 & -1 & \vdots & -\Delta^{-1} \end{array}\right] \end{array} \tag{6}$$

The bottom row line is the faulty component equation and the right most column corresponds to the extra fault variable. As seen in (6), for each faulty component there is an additional column at the right side and row at the bottom of the coefficient matrix is introduced. The faulty system with the FRS in matrix form is,

$$\begin{bmatrix} A & c \\ r & \Delta \end{bmatrix} \begin{bmatrix} X_f \\ \phi \end{bmatrix} = \begin{bmatrix} Z \\ 0 \end{bmatrix} \quad (7)$$

where c and r are the additional column and row introduced corresponding to a faulty component. The additional column c indicates the location of the faulty component. The additional row r is the faulty component equation with its node voltages. The value of Δ depends the faulty value of the component. It can be observed that a new variable called fault variable (ϕ) is also introduced as unknown into the unknown vector matrix (X_f) of the faulty circuit. It can also be noted that this fault variable is the unknown branch current. As seen in (7), the coefficient matrix (A) of the nominal circuit is retained in forming the faulty system equation without any modification in the values of it. Thus from (7), the faulty circuit equations are written as,

$$AX_f + c\phi = Z \quad (8)$$

$$rX_f + \Delta\phi = 0 \quad (9)$$

replacing $Z = AX$ from (1),

$$AX_f + c\phi = AX \quad (10)$$

$$A(X - X_f) = c\phi \quad (11)$$

$$X - X_f = A^{-1}c\phi \quad (12)$$

$$X - X_f = T\phi \quad (13)$$

$$\phi = (X - X_f)/T \quad (14)$$

$$T = A^{-1}c \quad (15)$$

The product $A^{-1}c$ is a complex column vector and it is called test vector as explained by Jose A. Soares Augusto in [7]. As c describes the location of a component in the CUT, the test vector is associated to that component and the values are independent of the faults. And it can be observed that the test vectors are associated to a specific component in the CUT and also the diagnosis variables. And it can also be observed that the test vector is sensitive to circuit component values (A is the circuit component matrix) as well as test frequencies.

3. TEST FLOW

The proposed test process starts with the simulation of CUT to derive the circuit parameters and consists of two stages such as pre testing stage and testing stage. In the pre testing stage, the circuits parameters such as node voltages and currents are derived and the test vectors at the test frequencies as in (15) are generated and stored. Based on the values of test vectors the diagnosis varaiables or test variables are selected. This is shown in fig.2.

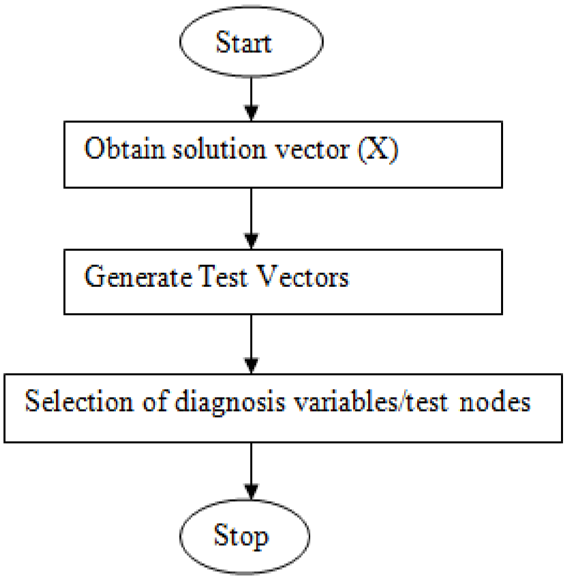

Fig-2: Pre testing stage

3.1 Selection of Diagnosis Variables or Test Variables

The diagnosis variables or test variables are selected based on the criteria that the nodes of corresponding diagnosis variables are accessible and at the same time the diagnosis variables must be useful in detecting more number of faulty components. The test vectors are used in identifying the right diagnosis variables for testing and no specialized approaches or methods are required for selection of diagnosis variables. The diagnosis variables with same test vectors are avoided as this limits the fault diagnosability of the components as it introduces same variation in the fault variables corresponding to the components of CUT. The faulty conditions of the components with same test vectors cannot be detected and they form ambiguity sets as explained by Jose A. Soares Augusto in [7]. Two or more circuit components belong to same ambiguity set if a fault cannot be identified between them.

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The testing stage consists of application of test signal at different frequencies selected within the bandwidth of the CUT at the input node and measurement of the selected diagnosis variables. The fault variables corresponding to the components of CUT are derived from (14) and as the testing is done at multiple frequencies, the average and relative standard deviation related to the average value of the fault variables derived at each frequency is found. An average relative standard deviation value of all the fault variables is estimated and used as a threshold for identification of faulty components. A component is said to be faulty if the relative standard deviation of the fault variable corresponding to that component is less than the threshold estimated. This is explained in fig.3 and the results obtained are explained in section 4.

4. ILLUSTRATIONS

The proposed approach is validated through the simulation results of the CUT. Transistor amplifier circuit shown in fig.4 is being used as the circuit under test. The test vectors are derived from the simulation of the CUT and as in (15) and are shown in chart 1 (only for the diagnosis variables & only the magnitude). The diagnosis variables (only the magnitude) are selected based on the discussion in 3.1 and are the node voltage V_5 & the currents at the nodes 1 and 2 (I_1 & I_2). Transistor is assumed to be fault free and the device parameters are, β=150, the total input capacitance is 0.258nF. A sinusoidal signal source with 0V DC and 1V AC is used to apply the test signal at node 2 and this source coupled to the base of the transistor through a coupling capacitor of 0.2μF. Four test frequencies within the bandwidth of the amplifier are selected (50 kHz, 100 kHz, 150 kHz & 200 kHz) for testing. The components are shown with their nominal values in fig. 4.

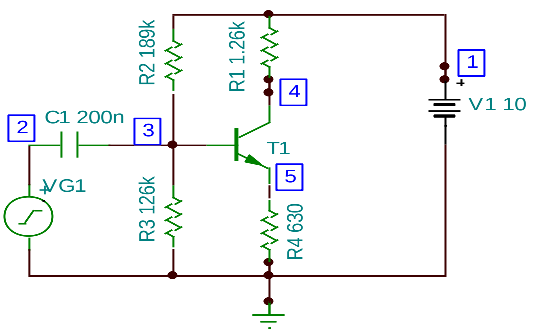

Fig-4: Transistor Circuit

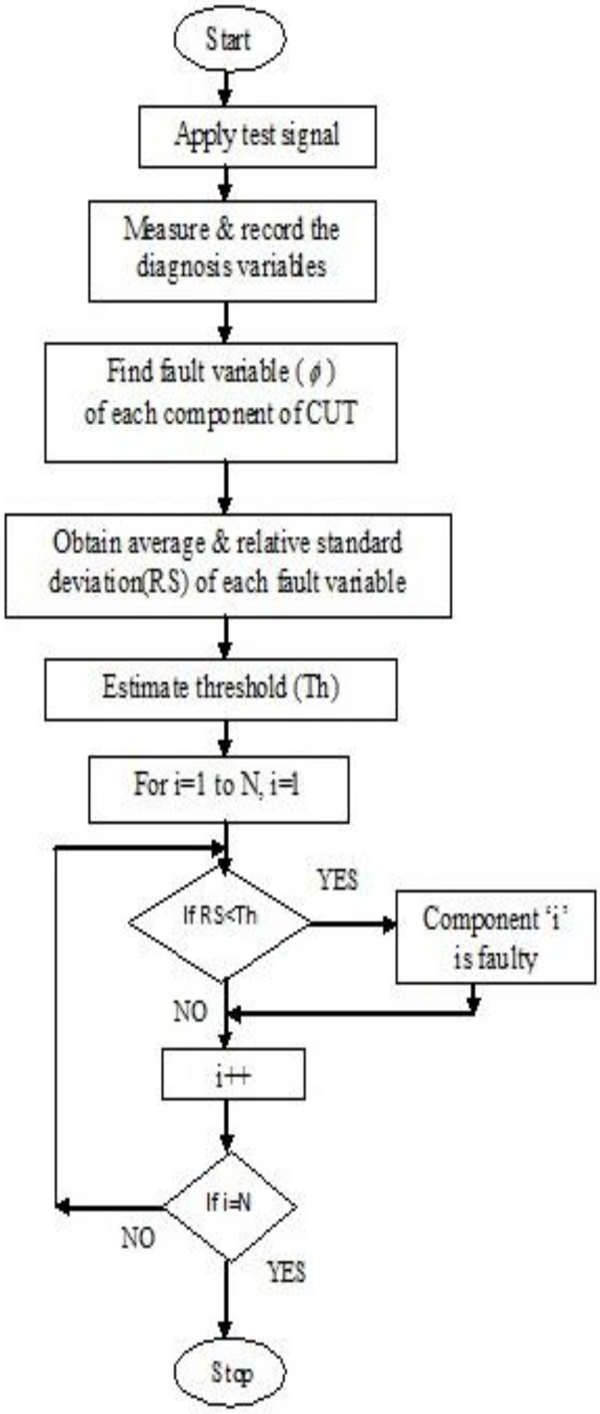

Fig- 3: Test Stage

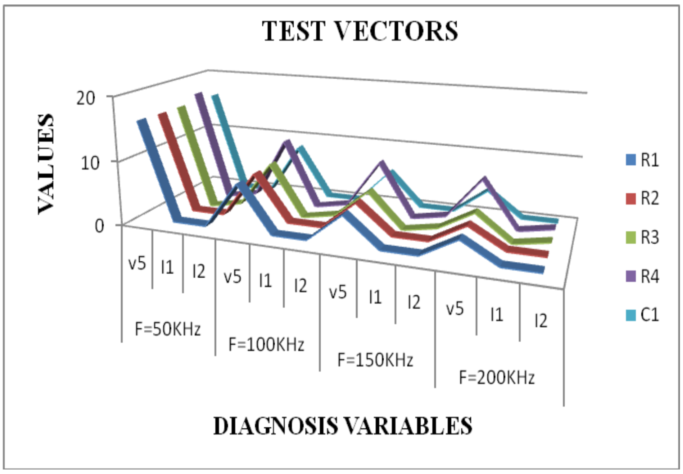

Chart - 1: Test Vectors

Fault detection is performed as explained in fig. 2 & fig.3. The components R_1 & R_2 with the faulty values 200kΩ & 100kΩ are introduced into the CUT and the fault variables are estimated at test frequencies. Average and standard deviation of the fault variables (corresponding to the components of CUT) at the test frequencies are estimated as 0.00052, 0.000152, 1.2, 0.986, 0.85 (R_1,R_2,R_3,R_4 &C_1). The threshold is the average of all these values and it is 0.609. From the values it can be identified that the components R_1 & R_2 are the faulty components because the fault variables corresponding to these components are lesser than the threshold. Results are shown in table 1 for some of the faulty conditions.

5. CONCLUSION

A test approach based on test vectors and multiple frequency measurements is proposed to locate multiple parametric faults in nonlinear analog circuits. The diagnosis variables for testing are selected based on the test vector values without the use of specialized approaches. From the test vectors it is also possible to identify the possible components that can be detected under faulty conditions. To locate multiple faults simple thresholding technique is used. It has been found that the approach is suitable to detect maximum of three faulty conditions which is because of the threshold value chosen.

Table -1: Simulation results of Transistor amplifier circuit

Faulty component and its value	Relative standard deviation of fault variables of components of CUT					Threshold
	R_1	R_2	R_3	R_4	C_1	
R_3 (50kΩ), R_4(100Ω)	0.795	0.633	0.28	0.00346	0.997	0.533
R_1(500Ω), C_1(150nF)	0.584	1.02	0.658	0.755	0.000274	0.603
R_2(150kΩ), $_1$(300nF)	1.42	0.584	0.716	0.755	0.0003	0.694
R_2(100kΩ), R_4(1000Ω)	1.22	0.353	0.853	0.004	0.966	0.679
R_3 (80kΩ), R_4(1500Ω) C_1(250nF)	0.954	0.985	0.334	0.542	0.000274	0.563
R_1(2000Ω), R_2(250kΩ) R_3 (100kΩ)	0.626	0.749	0.00321	0.898	1.61	0.773
R_3 (55kΩ), R_4(50Ω) C_1(180nF)	0.906	0.886	0.423	0.5	0.0004	0.543
R2(250kΩ), R3 (55kΩ) R4(50Ω)	0.795	0.00015	0.0032	0.0045	1.03	0.367
R_1(800Ω), C_1(250nF) R4(150Ω)	0.11	0.925	0.716	0.319	0.281	0.47

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