Entropy-Based Optimum Test Points Selection for Testing of Mixed Signal Circuits

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Abstract **--This paper proposes a method to select optimum number of test nodes in an analog Integrated circuit for fault diagnosis, using entropy computation. The algorithm estimates the probabilities in accordance with the cardinality of ambiguity sets. The optimum selection of test point reduces the test cost by reducing the redundant measurements. The Circuit Under Test (CUT) used in this work is analyzed by predefined sinusoidal input signal and voltages are measured at various nodes and fault dictionary is constructed under fault free and faulty conditions. In fault dictionary, the set of faults which have almost the same fault signatures are identified as ambiguity sets. The minimum node selection approach to fault diagnosis has been optimized using the concept of sub-ambiguity tables. In this proposed method, it has been shown that the number of test nodes required to diagnose faults has been significantly reduced and also time taken for simulation has been reduced.**

Keywords—Fault Dictionary, Integer coded fault dictionary, Entropy based Test point Selection.

I. INTRODUCTION

Testing of analog and mixed signal circuits has become gained more attention in the last decade for many reasons including increasing the applications of the analog circuits, integrating the entire system on one chip, and the cost of testing of analog circuits high compared with digital circuits testing For digital circuits, algorithms for the generation of test patterns based on gate-level net-list exist since as early as 1960's. Without the so-called Automatic Test Pattern Generation (ATPG) methods, it would not have been possible to produce the large digital ICs of the last twenty years at reasonable costs and quality. A similar test generation solution for analog testing became necessary with the increasing integration of analog and digital functionality on one chip. The analog test community has also been aiming at a solution comparable to that in digital, but the analog version of the problem is not solvable by similar analytical techniques. In the case of digital circuits, the discreteness in time and signal values, the well-defined fault propagation paths and topological boundaries of fault influence have simplified the problem to some extent when compared to the analog case.

Comparing with the digital circuits, fault diagnosis and testing for analog circuits are particularly challenging with the following reasons

- The parameters of analog components are usually continuous, which can change from zero to infinite, it is impossible to define any unified fault model for them.
- Meanwhile, in practical analog circuits testing, the information used in the diagnosis is not enough because of the large number of test nodes.
- Furthermore, there are non-linearity problem and feedback loop in analog circuits, it sharply increases the difficulty of the diagnosis.
- In addition, tolerance effects of the analog components are hard to eliminate, so the fault location is not precise but with some fuzzy result.

The material in this paper is arranged in the following order. In Section II of this paper, the Fault diagnosis techniques are briefly described. Section III discusses the entropy based approach. Section IV discusses the example circuit taken for describing the proposed algorithm. In Section V Conclusion and Future work are discussed.

II. FAULT DIAGNOSIS TECHNIQUES

Algorithms are developed by aiming at diagnosing component failures on Printed circuit board (PCB) that can be applied to identify the faulty components in analog ICs. Due to the limited accessibility to internal nodes in analog ICs, more number of algorithms, theoretical concepts has been developed during past three decades.

The testability concepts tells whether a given Circuit Under Test (CUT) is testable or not, whereas the degree of algorithm complexity tells about the effectiveness of an algorithm proposed..

Analog fault diagnosis methods are generally classified into Simulation-After-Test (SAT) and Simulation-Before-Test (SBT).

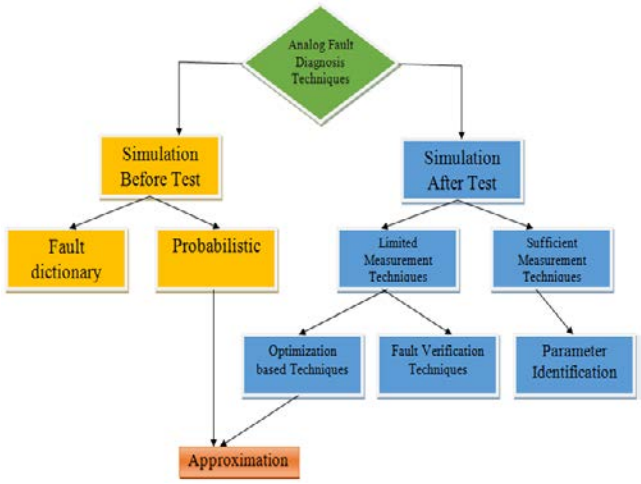

Fig. 1 Classification of Fault Diagnosis Techniques

SAT methods focus on parameter identification and fault verification and they are very efficient for diagnosis of soft faults because they are based on linear network models. In SAT namely parameter identification (based on the type of equations used in the fault diagnosis) and fault verification are discussed. In parameter identification major problem is the accessing of test points. However, Test point selection is NP-Hard Problem. Major disadvantages of SAT approach are high computational complexity, inability to deal with catastrophic faults.

SBT Techniques are used in design stage which allows building a time efficient system of testing.Fault dictionary is an important method of this category .Fault dictionary is a collection of measurements of a network under different potential faults.Selection of test measurements. The measurements may be node voltages, branch currents, source currents, etc. The Overview of the SBT Technique is shown in Fig. 2

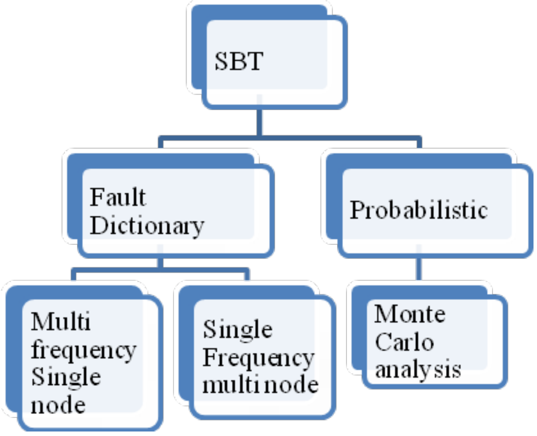

Fig. 2 SBT Technique Overview

The number of test measurements are chosen such that all or maximum number of faults are diagnosed. This criterion may sometimes drastically increase the size of the fault dictionary. Optimization is done to remove the measurements which are redundant or that do not help in fault isolation.

Due to the inherent properties of the analog circuits, the measurements made are sometimes similar for different fault conditions or the values are very near to each other. This gives similar fault signatures for different faults, thus making fault diagnosis difficult. All those measured values which are either same or very close in range are termed as ambiguity sets, as these measurements lead to an ambiguous result. For a circuit under test, there can be many ambiguity sets. To distinguish between these sets, integer codes are proposed by Lin and Elcherif [2].

Optimum selection of test points is, therefore, important to reduce the computation cost by reducing the dimensionality of the fault dictionary. Simultaneously, optimum selection of test points reduces the test cost by eliminating redundant measurements.

A .Fault Wise Table

For a given network, voltages or currents can be measured or simulated at the accessible test nodes to determine the network characteristics. Suppose that the voltage of a given network is analysed for the nominal case as well as for a set of faulty conditions. At any given node, various faults may give rise to voltage values which are very close to each other, and hence it may not be possible to clearly identify the specific faulty conditions. These faults are said to be in the same ambiguity set associated with a particular node. Babu et al. considered test point selection for the dictionary approach [4].

B. Integer Coded Dictionary

There is an important phenomenon which is commonly encountered and difficult to solve in analog testing and fault diagnosis: measurement ambiguity. Distinct faults may result in the measurements whose values are close to each other. Therefore, it is difficult to clearly recognize the specific fault. Such faults are said to be in the same ambiguity set associated with a specific measurement. The concept of an ambiguity set was first introduced by Hochwald and Bastian [1]. For the optimum test points set to distinguish the ambiguity sets, the integer-coded dictionary was first proposed by Lin and Elcherif [2] and subsequently researched by Prasad and Babu [4]. This approach proved to be an effective tool for the optimum test point’s selection. The two-dimensional integer-coded dictionary, or fault-wise table, is constructed as follows. Its rows represent all the potential faults (including fault-free case) while its columns represent all the available test points. For each test point, different ambiguity sets are classified based on computer simulation according to a preset criterion. A specific integer code is then assigned to each ambiguity set. Thus, the entries of the dictionary correspond to the simulated system responses. Note that for a given test point, distinct ambiguity sets have distinct integer codes. However, the same integer code can be assigned to different ambiguity sets associated with different test points, because each test point is an independent measurement and ambiguity sets for the same test points are independent.

III. ENTROPY BASED APPROACH

Test points selection techniques can be classified into two categories: inclusive and exclusive [4]. For the inclusive approaches, the desired optimum set of test points is initialized to be null, then a new test point is added to it if needed. For the exclusive approach, the desired optimum set is initialized to include all available test points. Then a test point will be deleted if its exclusion does not degrade the degree of fault diagnosis.

In the inclusive methods, redundant test points could be included in the selected test nodes. Since new test points are added sequentially, a test point may become redundant after new test points are added. In the exclusive methods, all redundant nodes are removed, but exclusive methods require longer calculation time than the inclusive methods. To achieve highest degree of fault coverage, a new method based on the Computation of entropy is proposed. This method belongs to inclusive approach which provides optimal set of test nodes.

The dominant idea of the proposed method is to evaluate the probability for each fault to be separated in accordance with the cardinality of each ambiguity set. Let, Si is the ambiguity set, nj is the test point, N_{opt} be the Optimal test point set.

Let, assume that Fij (i=1,2,...k) is the number of elements in the ambiguity set Si for test point nj. The probability of occurrence of an element chosen from ambiguity set Si is approximated by Fij/F. So the entropy based measure for any chosen test point nj is expressed by,

$$I(j) = -\{\frac{F1j}{F}\log\frac{F1j}{F} + \frac{F2j}{F}\log\frac{F2j}{F} + \cdots.. + \frac{Fkj}{F}\log\frac{Fkj}{F}\}$$

$$= \log(F) - \frac{1}{F}\sum_{i=1}^{k} F_{ij}\log(F_{ij}) \quad (1)$$

Since, in a given fault dictionary problem the number of selected faults F is fixed, the information content for the selected test point nj in is maximized upon minimization of the following entropy index,

$$E(j) = \sum_{i=1}^{k} F_{ij}\log(F_{ij}) \quad (2)$$

The physical explanation of is the information I(j) used to be captured from imprecise knowledge that test point nj contains. Because the number of all faults in a given dictionary is constant, the information content I(j) for the specific test point n(j) in Eqn(1) is maximized with the minimization of the entropy index E(j) . If a test point nj with the minimum value of E (j) is added to the desired test point set N_{opt} by inclusive approach, this will guarantee the maximal increase of information in N_{opt} by the maximal decrease of the entropy index. Consequently, this inclusive strategy guarantees that the maximal degree of fault diagnosis is achieved at each stage of test point inclusive selection.

Algorithm

Step 1: Construct fault dictionary In order to obtain test measurements, a sine wave with 4 volts amplitude and 1 kHz frequency was applied to the input of the active filter Circuit and the voltages were measured at nodes V1 through V11.
Step 2: Construct the integer coded fault dictionary and construct the ambiguity groups.
Step 3: Calculate the entropy values for corresponding nodes. Initialize an empty list of selected test points.
Step 4: Find the node which have Minimum entropy (E (j)).
Step 5: Include the node in the selected test point set.
Step6: Put nodes in order according to their importance ambiguity set size per eliminate the faults which are uniquely isolated.
Step7: Partition the fault-wise table according to the ambiguity sets for the selected set of test points.
Step 8: If the E (j) is zero for all j or if the new E(j) is the same as the previous E(j) for all j, then stop. Otherwise repeat steps 3 to 7 until minimal test set is obtained.

IV. EXPERIMENTS

In order to illustrate the entropy based test point selection, let us consider the active filter shown in Fig.3 Nominal parameter values are indicated on the circuit diagram. In this example 18 catastrophic faults are considered together with the nominal case to formulate the fault dictionary and all 11 nodes are assumed to be accessible for the purpose of demonstration.

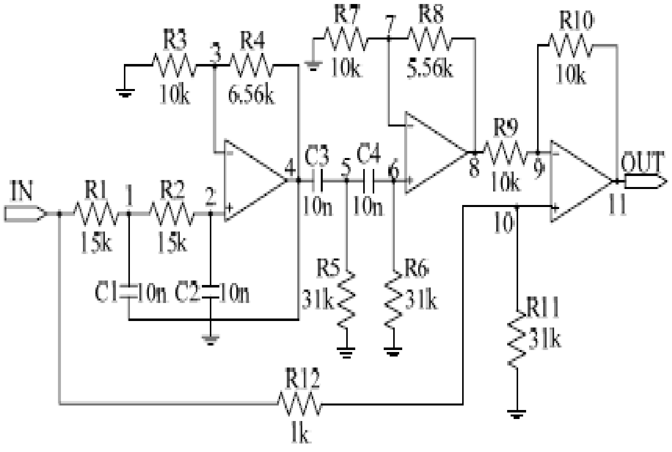

Fig. 3 Active Band Pass Filter

The integer coded dictionary for the active band pass filter is indicated in Table 1.

In order to obtain test measurements, a sine wave with 4 volts amplitude and 1 kHz frequency was applied to the input of the active filter circuit and the voltages were measured at nodes V1 through V11. Test point selection is performed to find the minimum number of tests (from voltage measurements at nodes 1 through 11) such that the analog system is diagnosable.

Table 1
Integer Coded Fault Dictionary

fault class	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	n11
f0(fault free)	3	2	2	3	3	3	3	4	1	1	0
f1(R1 open)	0	0	0	0	0	0	0	0	1	1	6
f2(R1 short)	3	2	2	3	3	3	3	4	1	1	0
f3(R2 open)	1	0	0	0	0	0	0	0	1	1	6
f4(R2 short)	2	3	3	4	5	4	5	5	1	1	4
f5(R3 open)	1	1	1	1	1	1	1	1	1	1	4
f6(R4 open)	0	0	0	2	2	2	2	3	1	1	7
f7(R5 open)	3	2	2	3	4	4	5	5	1	1	2
f8(R5 short)	3	2	2	3	0	0	0	0	1	1	6
f9(R6 open)	3	2	2	3	6	5	6	6	1	1	5
f10(R6 short)	3	2	2	3	2	0	0	0	1	1	6
f11(R7 open)	3	2	2	3	3	3	4	2	1	1	2
f12(R7 short)	3	2	2	3	3	3	0	7	5	1	8
f13(R8 open)	3	2	2	3	3	3	4	7	2	1	8
f14(R9 open)	3	2	2	3	3	3	4	4	1	1	1
f15(R9 short)	3	2	2	3	3	3	4	4	4	1	8
f16(R10 open)	3	2	2	3	3	3	4	4	2	1	8
f17(R11 open)	3	2	2	3	3	3	4	4	3	2	1
f18(R12 open)	3	2	2	3	3	3	4	4	0	0	3

In the Table 1, f0 is the nominal value, f1-f18 are open & short faults; n1-n11 are the nodes which are used for measurement. After calculating the size of each ambiguity set, the entropy index value E (j) is indicated in Table 2.

Table 2
Entropy Index Values for First Iteration

Test nodes	n1	n2	n2	n4	n5	n6	n7	n8	n9	n10	n11
Entropy Indices	17.2	16.5	17.47	16.64	12.63	12.2	11.32	9.528	15.08	20.9	**7.2**

From Table 2 the nodes which contain minimum entropy n11 is identified. The node n11 is added to desired optimum set N_{opt} = {n11}.Since the stop condition is not satisfied the algorithm continues. Node will not be considered for the computation of entropy indices in the remaining iterations of the algorithm. According to the ambiguity sets of n11, the integer coded dictionary is partitioned into 9 sub groups. It is indicated by Table 3.

Table 3
Partitioned Integer-Coded Dictionary for the First Iteration

Fault	n11	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10
F0	0	3	2	2	3	3	3	4	4	1	1
F2	0	3	1	2	3	3	2	3	4	1	1
F14	1	3	2	2	3	3	3	4	4	1	1
F17	1	3	2	2	3	3	3	4	4	3	2
F7	2	3	2	2	3	4	4	5	5	1	1
F11	3	3	2	2	3	3	3	4	2	1	1
F18	3	3	2	2	3	3	3	4	4	0	0
F4	4	2	3	3	4	4	4	5	5	1	1
F5	4	1	1	1	1	1	1	1	1	1	1
F9	5	3	2	2	3	5	5	6	6	1	1
F1	6	0	0	0	0	0	0	0	0	1	1
F3	6	1	0	0	0	0	0	0	0	1	1
F8	6	3	2	2	3	0	0	0	0	1	1
F10	6	3	2	2	3	2	0	0	0	1	1
F6	7	0	0	0	2	2	2	2	3	1	1
F12	8	3	2	2	3	3	3	0	7	5	1
F13	8	3	2	2	3	3	3	4	7	2	1
F15	8	3	2	2	3	3	3	4	4	4	1
F16	8	3	2	2	3	3	3	4	4	2	1

The Faults F7,F9, F6 are Uniquely isolated and are removed from the Table. Again calculating the size of each ambiguity set , the entropy index value E(j) is indicated in Table 4.

Table 4
Entropy Index Values for Second Iteration

Test nodes	n1	n2	n2	n4	n5	n6	n7	n8	n9	n10	n11
Entropy Indices	4.18	4.816	5.42	5.645	5.645	6.84	5.04	4.816	**4.21**	6.02	.....

After second iteration Node n9 have the minimum entropy value. It is then included in desired optimum set after n11.

Table 5
Partitioned Integer-Coded Dictionary for the Second Iteration

Fault cases	n11	n9	n1	n2	n3	n4	n5	n6	n7	n8	n10
F0	0	1	3	2	2	3	3	3	3	4	1
F2	0	1	3	2	2	3	3	3	3	4	1
F14	1	1	3	2	2	3	3	3	4	4	1
F17	1	3	3	2	2	3	3	3	4	4	2
F11	3	1	3	2	2	3	3	3	4	2	1
F18	3	0	3	2	2	3	3	3	4	4	0
F4	4	1	2	3	3	4	5	4	5	5	1
F5	4	1	1	1	1	1	1	1	1	1	1
F1	6	1	0	0	0	0	0	0	0	0	1
F3	6	1	1	0	0	0	0	0	0	0	1
F8	6	1	3	2	2	3	0	0	0	0	1
F10	6	1	3	2	2	3	2	0	0	0	1
F12	8	5	3	2	2	3	3	3	0	7	1
F13	8	2	3	2	2	3	3	3	4	7	1
F15	8	4	3	2	2	3	3	3	4	4	1
F16	8	2	3	2	2	3	3	3	4	4	1

The Faults F14, F17, F11, F18, F12, F13, F15, F16 are uniquely isolated and are removed from the Table. Again calculating the size of each ambiguity set, the entropy index value E(j) is indicated in Table 6 .

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Table 6
Entropy Index Values for Third Iteration

Test nodes	n1	n2	n2	n4	n5	n6	n7	n8	n9	n10	n11
Entropy Indices	**1.204**	1.806	1.806	1.806	2.033	3.01	3.01	3.01	…….	6.02	…….

Table 7
Partitioned Integer-Coded Dictionary for the Third Iteration

Fault class	n11	n9	n1	n2	n3	n4	n5	n6	n7	n8	n10
F0	0	1	3	2	2	3	3	3	3	4	1
F2	0	1	3	2	2	3	3	3	3	4	1
F4	4	1	2	3	3	4	5	4	5	5	1
F5	4	1	1	1	1	1	1	1	1	1	1
F1	6	1	0	0	0	0	0	0	0	0	1
F3	6	1	1	0	0	0	0	0	0	0	1
F8	6	1	3	2	2	3	0	0	0	0	1
F10	6	1	3	2	2	3	2	0	0	0	1

The Faults F4, F5, F1, F3 are uniquely isolated and are removed from the Table. Again calculating the size of each ambiguity set, the entropy index value E(j) is indicated in Table 8 .

Table 8
Entropy Value after Each Iteration

Test nodes	n1	n2	n2	n4	n5	n6	n7	n8	n9	n10	n11
Entropy Indices E(j)	17.2	17.477	17.477	16.64	12.03	13.01	10.61	9.528	15.08	20.9	**7.2**
	4.18	5.41	5.42	5.645	5.645	6.622	5.64	4.816	**4.21**	6.02	.....
	1.204	1.806	1.806	1.806	2.033	3.01	3.01	3.01	....	6.02	....
	......	1.024	1.024	1.024	**0.6**	1.024	1.024	1.024	....	1.204	....

The final solution is found to consist of the set of nodes {N11, N9, N5, and N1} which is the same result as obtained by the proposed algorithm. However, the computation time of the exclusive algorithm in is much longer. The programs are simulated using MATLAB 2015a version.

V. CONCLUSION

In this paper, a new method based on entropy based test point selection is proposed. This approach uses integer coded fault dictionary construction and entropy is computed. The minimum entropy test node is selected. Computation time is proportional to the number of potential faults and the number of available test points. In this work we assumed that the all the test nodes are available for measurement, but it is not a practical one. The method proposed in this paper, not only reduce the number of test points, but also reduce the size of the fault dictionary .The major advantage of the method is highly efficient and time for testing also reduced.

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