Use of Artificial Intelligence Techniques to Fault Diagnosis in Analog Systems

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Abstract: - Basic concepts of fault diagnosis in analog and mixed (analog and digital) electronic systems by means of the simulation-before-test approach, the so called dictionary approach, have been presented. Special attention has been paid to application of artificial intelligence tools, such as: artificial neural networks, fuzzy sets and evolutionary computing.

Key-Words: - Analog electronic fault diagnosis, parametric faults, artificial intelligence.

1 Introduction

Automated testing and fault diagnosis of devices are fundamental topics in the development (design, production) and maintenance of safe and reliable complex systems. They are major steps in all production industries, and especially in electronic systems production. Such systems can be constructed almost entirely with digital components, however many systems still have analog components [Bur01]. The digital part can be tested with practically verified standard methods, aided by automatic test pattern generator and Built-In-Self-Test (BIST) [Bak96], [Ric98]. Testing the analog part is less well understood. Since 1970’s, analog fault diagnosis has become an active research area. Two major issues make the diagnosis particularly difficult: unknown deviation in tolerances of nonfaulty components and very complex nature of faults [Mil98]. They generally fall into two categories: catastrophic or hard faults and parametric or soft faults. It is claimed that 80-90 percent of analog faults involve shorted and opened resistors, capacitors, diodes and transistors [Mil89], i.e. catastrophic faults. Moreover, in case of mixed integrated circuits (ICs), the cost of the test process is about 30% of the production costs and it is estimated that 80% of costs refers to analog part which occupies less than 10% of the substrate. The theoretical foundation of analog fault diagnosis is primarily laid, although there is still a long way to go for practical applications.

The load board connects the Device Under Test (DUT) to the tester resources (test program + test hardware) and all the performed tests fall into two categories: Specification Driven Tests (SDT) and Fault Driven Tests (FDT) [Hue93]. The SDT or functional tests are those which measure the DUT dynamic behaviour. The FDT or parametric tests measure the DUT responses (node voltages) for given test stimulus or stimuli, and then, component fault can be detected, and eventually further classified, located and identified. In the high level secure and safe systems, like in aviation or aeronautics, the prediction of all faults are obligatory. The pyramid in the fig. 1 shows the low level test up to high level diagnostic with fault localization and identification.

Today, Time-To-Market (TTM) seems to be the most important factor of a design-production process, and thus, time costly SDT have to be preceded by simple and fast FDT [Mil94]. Two different approaches to FDT can be distinguished: Simulation-Before-Test (SBT) and Simulation-After-Test SAT [Ban85]. In the SAT approach fault isolation is obtained by estimating the DUT parameters from the measured responses. All the calculations are performed on-line, after the test, what makes this approach very time consuming, and thus, impractical at a production stage of the DUT life. The SBT approach is based on comparison of the DUT responses associated with predefined test stimulus or...
stimuli with those induced by different fault conditions and stored in the so called Analog Fault Dictionary (AFD). A subsequent classification must be performed to solve a fault detection and eventually location problems. Data obtained from the DUT simulations and stored in the dictionary are collected in the so called signatures. Nowadays, there is a common opinion that the SBT approach should be preferred for both, prototype diagnosis and production tests [Rut03]. In this approach all the simulations are performed off-line, at the dictionary construction stage, i.e. at the before-test-stage, not during the test application stage [Hue93].

Main steps of AFD construction have been presented in Fig. 2.

Generally speaking, the selected classifier designates the AFD type and four types can be distinguished:

1. “Classical” dictionary, Nearest Neighbour Rule (NNR) classifier and real number signatures.
2. Integer-code-dictionary, classifier based on ambiguity set concept and integer-code signatures.
3. Dictionary with Artificial Neural Network (ANN) classifier, single integer signature or binary-code signatures.
5. Transmittance dictionary, algebraic expression type signatures.

It can be considered that the post-test fault diagnosis is the problem of pattern recognition and use of Artificial Intelligence (AI) techniques has been proposed in 1989 [McK89], and then developed extensively by many researches. The first obtained results seem to be very promising and application of these techniques to AFD problems will be discussed in the section 2. Before then, fundamental concepts of fault, error and failure will be explained. There is a cause-effect relationship between them, as shown in Figure 3, where the main agents provoking a fault are depicted as well. Fault is a physical defect, imperfection or flaw that occurs within a component and causes deviation of its parameter outside the tolerance region. Fault in the DUT can be detected (GO/NO GO test) and eventually located. Error is the manifestation of fault. It is a short or open circuit, in case of hard fault or parameter deviation from nominal value, in case of soft fault. Component error can be identified, i.e. short can be distinguished from open or soft deviation value can be determined. This last identification is practically limited to SAT techniques. Failure can be either the non-performance of some action that is due or expected or the performance of a function in a subnormal quality or quantity. The DUT fault and error can be diagnosed by means of the FDT, while failure by means of the SDT. It should be mentioned, that the DUT with faulty component may not exhibit failure!

2 Usage of Artificial Intelligence techniques to FD construction

Main problems of analog test program development and AFD construction generally fall into two categories:

1. before-test optimisation of the testing effort (testing time + test equipment complexity), i.e. optimally selection and ordering of tests and minimization of test points (test nodes + test stimuli parameters),
2. classification of signatures (pattern recognition).

Both problems can be well solved by means of the AI tools, such as: Artificial Neural Networks (ANN), Evolutionary Computing (EC) and Fuzzy Systems (FS).

2.1 Testing effort optimisation

Testing effort optimisation is one of the main problems of AFD construction. This optimisation comprises: 1) test program development, i.e. stimuli selection, 2) test points selection. These problems are very similar. They belong to the NP hard class of problems and only
heuristic procedures are possible. These procedures can be grouped in three categories:
- procedures based on engineer’s intuition [Hoc79], [Pra00],
- procedure based on information theory and information channel concept [Rut93], [Star04], [Gol06],
- procedures based on EC [Gol02a,b], [Rut03], [Rut04], [Puc04], [Gol07].

These last procedures seem to be very effective. However, time effort of evolutionary procedures is normally much greater than those of other optimisation procedures, but the obtained results are usually better and it should be emphasized, that computer time spent at the before-test stage is of the less importance and can be accepted as long as it is contained within a reasonable limit.

2) Test points optimisation

Selection of the minimum set of test points, i.e. test nodes from all accessible nodes and values of stimulus parameters from all proposed values, that provide the assumed diagnostic information is one of the main problems of the AFD construction. It seems that entropy based procedure [Rut93,02], [Star04] and EC-aided procedure [Gol02a], [Puc04], [Puc06] are of equivalent effectiveness and prevail over the intuitive procedures [Hoc79], [Lin88], [Pra00]. All these procedures are based on measurement ambiguity sets conception. For each measurement, sets that contain indiscernible circuit conditions (ambiguity sets) have to be defined, what requires mapping of tolerance regions from parameter space to measurement space, for each simulated circuit condition. Simple heuristic procedure [Hoc79] and much more complex sensitivity analysis based procedure [Mil89].

Use of GA to test point optimisation has been proposed in [Gol02a] and [Gol07]. Single excitation has been assumed, what means that optimisation is limited to test nodes. In [Puc04], application of the algorithm has been extended into general case, i.e simultaneous optimisation of test nodes and values of stimulus parameter. Each gene of a chromosome codes one test point: 1=include; 0=exclude. Fitness function takes into account both, i) number of selected test points (weight of a chromosome) and ii) fault isolation rate. This rate is designated based on ambiguity sets assigned to individual test point (measurements). The obtained results have been compared with those obtained by means of information channel concept [Rut93], [Star04] and they proved the evolutionary approach effectiveness. By proper selection of the optimisation problem target function, i.e. fitness function of chromosomes, and its weights, prevalence of the diagnostic information obtained (fault isolation range) or testing effort (number of test points selected) can be established.

Today, because of IC element density, fault detection and location can be done by tests at a limited number of test nodes, practically limited to output connections. Thus, optimally selection of test signals and then, preliminary assumption of discrete values of their parameters, such as frequency of sinusoidal excitation, increase time of step excitation or width of pulse excitation, becomes the predominant problem of analog fault diagnosis. In [Gol02b], use of Evolutionary Strategy (ES) to optimally selection of step excitation increase time has been proposed and the obtained results have proved effectiveness of this approach. In ES genes are real numbers and this evolutionary technique seems
to be an ideal technique to solve these optimisation problems.

2.1 Testing effort optimisation

Fault definition and classifier selection are other main problems of the SBT technique. Fault definition is generally based on the design engineer’s experience and intuition, and no effective algorithmic methods are available so far. Normally, only catastrophic faults (more than 80 percent of all analog faults) are defined. Taking into account soft faults enormously increase size of traditional signature AFD (NNR based, integer-code). New, AI based classifiers (ANN, FS, transmittance - EC based) permit to avoid this deficiency. Fault classifier is the fundamental part of AFD. Good classifier should reveal generalization ability at the after-test stage, i.e. first of all it should provide good isolation of all simulated conditions (one “healthy” + F “faulty” conditions), at a presence of noise caused by design tolerances of nonfaulty elements, and eventually it should also detect some soft faults, especially significant faults from regions laid far away from tolerance region, e.g. (0, 0.5Xnom); (2Xnom, ∞). Other important feature of good classifier is minimum on-line time effort, i.e. from-test-to-decision time.

The most commonly used and the simplest NNR (Euclidean distance) based classifier demonstrates poor generalization ability and significant on-line computations, and then, it is not worth researchers’ attention.

Classifier based on ambiguity set conception and integer-coding of signatures requires very low on-line calculations (signatures are arranged in ascending order), however, its generalization ability is questionable, especially when heuristic procedure of ambiguity sets definition is applied.

In [Gol03] completely new approach to AFD construction has been proposed. In this approach classical signatures built of real, integer or binary numbers, have been replaced by transfer functions (transmittances) that express numbers, have been replaced by transfer functions: “low”, “normal” and “high”. For all values obtained from measurements is imprecise or in other words fuzzy. Mathematical description of such fuzzy information has been proposed by L.Zadeh [Zad65]. Then, it seems that embedding of fuzzy set theory to analog fault diagnosis is a natural approach. For the first time this approach has been proposed in 1979 [Lee79]. Measurements could be preprocessed by membership functions, however designation of their parameters is the main problem. In 2001, utilization of the DUT sensitivity has been proposed [Grz01] and [Grz06]. It has been assumed that each measurement is preprocessed by three gamma-trapeze membership functions: “low”, “normal” and “high”. For all parameters from tolerance region, measurement is “normal”, and “low” or “high” if one parameter is outside tolerance region. Parameters of these functions and IF-THEN decision rules are designated at the before-test stage, based on sensitivity analysis. Such fuzzy dictionary has two new features: capability of soft fault detection and partial identification, by designation of a sign of a parameter deviation outside tolerance margins.

Decidedly best features, both, best generalization ability and minimum on-line computations, reveal ANN classifiers, what has been claimed by many researchers. Over two past decades, the field of the ANN has shown many attractive features. One of the most enticing potentiality of ANN is their classification capabilities. Another attractive property of ANN is their learning and generalization capabilities. The mentioned properties make the ANN suitable for identification problems, and
so, offer the possibility to use them as classifier in AFD. The first attempts have appeared in 1989 and dealt with process fault diagnosis [Ven89] and medical diagnosis [Sca89]. The first application of ANN to electronic circuit diagnosis has been reported in 1990 [Rut90], [Spi92]. During the next years vast number of contributions have appeared. The following should be listed, [Mea91], [Spi92,97], Rut[92,95], [Mai97], [Mad99], [Ami02], [Grz05], [Grz06a]. Generally speaking, there are four types of ANN [Yan00]:
- back-propagation neural network (BPNN),
- probabilistic neural network (PNN),
- self-organizing map (SOM),
- radial basis function neural network (RBF).

It is difficult to state which type of ANN best suits analog fault classification. A PNN classifies data by estimating the class conditional probability density function. The first presented results [Yan00] are promising, however a PNN classifier practical effectiveness should be verified by other researchers. A SOM is known as a topological mapping algorithm, in which similar patterns cluster together automatically. Only few applications to analog fault classification have been reported [Col94], [Oso95]. Difficulty in determining the boundary on mapping space is the main drawback. A RBF is a feed-forward ANN and its application to analog fault classification has been proposed in [Cat02]. Optimally selecting the basis function for the classification problem is the main drawback. Great majority of contributions propose to use a BPNN as analog fault classifier and this approach seems to be the most promising. It seems, that by proper preparation of training set, input data preprocessing and output data coding very good isolation of simulated faults can be achieved in the presence of design tolerances. It has been suggested to split fault classification into two phases: 1) fault detection by means of GO/NO GO neural (single output) fault dictionary, 2) fault location by means of multi-output (signature) neural dictionary [Grz02]. This solution provides much better isolation of “healthy” condition, than in case of single, fault detecting and locating dictionary. It should be mentioned that training sets of both dictionaries are the same. As pointed out, AFD classifier input data preprocessing and output data coding are important problems to be solved by the design-engineer.

Input data preprocessing.

Normalization is the most commonly used technique of AFD input data (measurements) preprocessing [Ami02]. Standard normalization allows to equalize level of different input signals from a very wide range, but it fails when a single signal takes values from a wide range and distinction of both, “low” signals and “high” signals is the task.

In such case, granulation technique can be utilized [Rut92,95]. In this technique, each input signal is split into subinputs, each of them is responsible for one and only one decade of the signal.

Fuzzyfication is the other effective technique of input signal preprocessing. The technique has been proposed in 2001 [Grz02]. Each signal (measurement) is preprocessed by three membership functions “low”, “normal” and “high”. Parameters of these functions can be well defined by means of sensitivity analysis. It should be mentioned, that both, fuzzyfication and granulation preprocessing techniques also provide input data normalization.

Other input signal preprocessing techniques have been proposed, such as:
- wavelet transformation [Ami00],[Chru06],
- compression by means of principal component analysis [Mat96], [Ami02], [Ali02],
- bilinear transformation [Cza03],
- preprocessing by Linear Vector Quantization (LVQ) ANN [Rut94].

Application of these preprocessing techniques is usually limited to specialized circuits and they normally require greater on-line computations.

Coding of outputs.

Coding method of AFD outputs (signatures) is normally imposed by the used classifier. Each output (signature) of integer-code classifier (≠0,1,...,F) based on ambiguity set concept, is built of integers. Each digit (integer) of such output corresponds to one measurement, and for the given circuit condition, it is a number of ambiguity set that contains the condition. Each output of transmittance classifier takes real values from the range <-1,+1>; positive value indicates component fault occurrence. In BPN classifier, signatures are designated by the output layer. This layer can contain:
- one neuron with output taking binary values 0 and 1, for GO/NO GO test or integer values 0,1,...,F, for fault locating dictionary,
- F neurons with binary outputs, 1 at the f-th output means occurrence of the f-th faulty condition,
- K≥log₂(F+1) neurons with binary outputs, that code F+1 circuit conditions. Simple binary code is preferred. This way of BPPN classifier output coding seems to be the best, as it provides the best isolation of circuit conditions at minimum size of the output layer.

3 Summary

As pointed out, basic problems that have to be solved by the design engineer when constructing an AFD are: 1) stimuli selection, 2) test point optimisation, 3) fault definition, 4) selection of a classifier, 5) selection of an input data (measurement) preprocessing method, 6) selection of an output (signature) coding.
Different solutions of individual construction problems can be combined, what gives quite large number of combinations. Today, it is impossible to point out the optimal combination for the given diagnostic problem, for the specified DUT, at the given stage of its life. However, it seems that during prototype testing costly SDT nevertheless can be applied. Next, during the early stages of production simple dc tests should be applied (“bed of the nails” testing at wafer probe), followed by more complex sinusoidal and/or arbitrary stimuli tests. Finally, for mature products SDT or other tests (FDT) providing high diagnostic information should be performed. Generally, BPNN based classifier with input signal granulation and binary coding of outputs reveals the most advantageous characteristics, while EC techniques are the most suitable in solving test planning optimisation problems, i.e. test nodes and stimuli selection and test ordering. In Table 1 comparison of fault dictionaries with the practical goals has been presented. Generalization capability 1 means capability of fault isolation at a presence of design tolerances. Generalization capability 2 means capability of soft fault isolation.

Table I: Comparison of fault dictionaries with the practical goals.

<table>
<thead>
<tr>
<th>Fault Dictionary</th>
<th>on-line computations</th>
<th>generalization capability: hard/soft fault</th>
<th>global/multiple fault detection</th>
<th>module level diagnosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a Integer-code</td>
<td>minimal</td>
<td>Good/poor</td>
<td>difficult</td>
<td>difficult</td>
</tr>
<tr>
<td>2 Transmittance</td>
<td>low</td>
<td>Good/good</td>
<td>possible</td>
<td>possible</td>
</tr>
<tr>
<td>3a BPNN</td>
<td>minimal</td>
<td>Good/good</td>
<td>possible</td>
<td>possible</td>
</tr>
<tr>
<td>4 Fuzzy System</td>
<td>low</td>
<td>Good/good</td>
<td>difficult</td>
<td>difficult</td>
</tr>
<tr>
<td>5 Classical NNR</td>
<td>moderate</td>
<td>Poor/poor</td>
<td>difficult</td>
<td>possible</td>
</tr>
<tr>
<td>6 Practical goals</td>
<td>minimal</td>
<td>very good/very good</td>
<td>possible</td>
<td>possible</td>
</tr>
</tbody>
</table>

References:
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