Qualitative Dynamic Diagnosis of Circuits∗

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Abstract

We describe ACDS, an automatic diagnostic system. ACDS is capable of diagnosing faults on analog circuits in dynamic conditions. The circuit’s dynamic behavior is studied by means of a series of intrastate simulations during which the qualitative state of the circuit does not change.

An acquisition board collects the value of a set of quantities corresponding to accessible test points. These measurements are converted into qualitative values and are used for two purposes: first, to determine the state of the circuit components; second, to trigger the diagnostic procedure whenever a discrepancy between observed and predicted behavior is found.

The main difficulty in this phase of measurement interpretation consists in obtaining meaningful numerical–qualitative data conversion for values of quantities approaching a boundary between two different qualitative intervals.

System performance has been verified through a number of simulations, which have shown the proposed approach to be efficient both in terms of localized faults and of flexibility in adapting to different circuits.

1 Introduction

The problem of diagnosing faults in analog circuits is difficult to solve for many reasons [IEEE (1979), Bandler and Salama (1985), IEEE (1987)]: difficulty in measuring current without breaking connections, lack of good models for a broad class of faults, presence of nonlinearities, etc. Diagnosing analog circuits involves greater computational effort and costs than diagnosing digital circuits. For the above and other reasons, the technology of automated fault diagnosis in analog circuits has not progressed at any great pace and is still being developed. The main problem to be solved is to reduce computational complexity and enhance reliability in those cases where, due to tolerance, the circuit parameters are not known with precision.

In recent years research has focused on developing systems that reproduce the behavior of a diagnosis expert. These systems are provided with knowledge both of the heuristics (shallow knowledge) and of the device being diagnosed (deep knowledge) [Giovannini and Malabocchia (1985), deKleer and Williams (1987), Fanni et al. (1988), Dvorak and Kuipers (1989)]. Deep knowledge is often formalized in the model of the circuit, which may be quantitative or qualitative. Quantitative models contain a description of the structure and behavior of the circuit in terms of algebraic or differential equations; they are capable of exactly simulating the behavior

of the circuit in different situations. Qualitative models are not designed to provide an accurate description of the relations between the different parameters but rather to exploit the qualitative relations between them. However, they permit one to reason about the physical system like a troubleshooting expert, who exploits qualitative reasoning to isolate faults [deKleer and Brown (1984), Cunningham and Brady (1987), Dague et al. (1987), Cois et al. (1989), Dague et al. (1991)].

The diagnostic system developed here (ACDS: Analog Circuits Diagnostic System) uses qualitative reasoning to diagnose linear and non-linear analog circuits affected by single or multiple faults. The faults in analog circuits may be [Bandler and Salama (1985)]:

- catastrophic (or hard) faults, such as those due to short-circuits, open circuits, the breakdown of a component, that cause a sudden, large variation of a parameter;
- deviation (or soft) faults, that occur when a faulted component deviates slightly from its nominal value.

However, statistics show that catastrophic faults are responsible for 80-90% of failures in analog circuits [Hochwald and Bastian (1979)] and we chose to investigate this type of failure. This choice was dictated by the qualitative approach adopted, in that it does not allow for precise numerical values of the parameters concerned.

An earlier work [Cois et al. (1989)] describes a diagnostic system capable of locating faults through a qualitative analysis of the circuit in static conditions. ACDS has been implemented based on this previous experience, and permits automatic diagnosis of circuits in dynamic conditions on account of an acquisition module that allows certain parameters to be sampled in appropriate points.

The following are the key features of ACDS.

- The qualitative state of a variable generally takes values in the set \{-, 0, +\}. However, it may often be necessary to refine this simple partition of the real axis to better describe nonlinear components [Dague et al. (1987)]. As an example, the voltage at the terminals of a diode will take values in the set \{-, 0, + off, + on, + ko\} (see section 4 and section 6).

- We assume that the only measurable quantities are the voltages of a small number of test point nodes. In all practical applications, only a few variables may be observed [Dvorak and Kuipers (1989)]. Thus it is unfeasible to use a measurement generation module that sequentially chooses optimal, albeit unreachable, test points, as in deKleer and Williams (1987). We use an acquisition board to gather all available measurements almost simultaneously; the delay between the measurement in two test points is due to the sampling delay of the acquisition board.

- The behavior of each component is described by a set of confluences [deKleer (1984)] and by the knowledge of the qualitative state in which each confluence may be applied. After each set of measurements, the system computes the state of the components and selects the corresponding confluences to be part of the overall model of the circuit.

- The system does not perform interstate simulation, as in deKleer and Brown (1984). Each set of measurements, that may be regarded as a photograph of the state of the circuit, is used to perform an intrastate simulation that triggers the diagnostic procedure if a mismatch between observed and predicted behavior is found. The results of the
diagnosis do not depend on the order in which these photographs are taken. Each intrastate simulation increases the probability of detecting new conflicts and thus of improving the diagnosis.

- During the intrastate simulation, we do not use causal propagation heuristics, as in deKleer (1984). This ensures that the system is correct, i.e., all the deductions are correct, at the expense of non exhaustivity, i.e., not all that may be physically determinable is made explicit.

In the following, we describe the architecture of ACDS and discuss the results of numerous fault simulations performed on a circuit which is part of a speed control system for a DC motor.

## 2 Diagnostic Strategy

The diagnostic strategy implemented in ACDS may be schematized in broad lines as in Figure 1. As can be seen, it is based on detecting conflicts between the observed behavior of the circuit and the behavior predicted by the model. These conflicts, defined as sets of components that cannot be simultaneously sound without conflicting with the observed values, form the basis of the search for candidates. By candidate we mean a set of components that, being assumed to be malfunctioning, are able to justify all the measurements taken. A candidate is called minimal if it is not a superset of any other candidate.

This strategy, formalized independently by deKleer (1984), and Reiter (1987), is nothing more than an implementation of the more general strategy adopted by an expert in the manual diagnosis of a circuit. It allows the system to perform the diagnosis in an extremely flexible way, in the sense that it does not envisage a particular set of measures as input, but exploits all available information, and the lack of certain data will not make the others useless, as is usually the case in classic automatic procedures.

Clearly, this feature has its price in that the output of the diagnostic procedure is not the diagnosis, i.e., the set of components actually malfunctioning, but merely a set of candidates to which, in the strict sense, we are not even sure that the diagnosis belongs. In fact what ACDS generates, according to deKleer and Williams (1987), is only the set of minimal candidates. This strategy is based on the heuristic statement that if a fact can be explained in a simple way and in a complex way the best explanation is the simple one.

From the above emerge the two fundamental reasons justifying our statement on the intrinsic limits of the strategy employed here:

- The conflict generation procedure followed does not generate all possible conflicts, but only some of them, that derive from particular sets of measurements taken and from the ability of the simulator to be exhaustive (see next paragraph). This implies that the candidates obtained from these conflicts may not satisfy other existing though not made explicit conflicts.

- Even if the set of conflicts were complete, by considering only the minimal candidates, the set of candidates would be incomplete in any case.

Actually, as already mentioned, compared to other automatic diagnostic procedures, the above limits represent a more apparent than real disadvantage. In the real world, any method must
cope with the limitation and imprecision of available measurements and above all it must be able to actually realize highly complex calculation schemes, which involve simplifications and reductions that, in practice, do not guarantee reaching a diagnosis, even when theoretically possible. One merit of this procedure is that it makes explicit the heuristics used and, hence, the value and limits of the results achieved.

The differences between the implementation of deKleer and Williams’ strategy and ACDS warrant comment.

In the first case the diagnostic procedure is performed iteratively adding at each step the appropriate measurements chosen by a criterion not readily applicable, which tends to minimize the total number of measurements, and stops when, on the basis of heuristic criteria, the set of candidates determined is considered satisfactory.

In the system at hand, the measurements are chosen a priori in relation to the test points effectively available and the procedure as a whole is not repeated. In addition we use qualitative analysis in simulating the correct behavior of a circuit. Problems related to the acquisition and qualitative interpretation of measurements are discussed in Dague et al. (1987), DeCoste (1991), Raiman (1991).

3 Architecture

The architecture of the system which implements the diagnostic strategy described above is schematized in Figure 2. The ACDS consists of three basic modules which will be described in detail below. The acquisition module and the diagnostic module are the ones that act in the diagnostic stage proper (on line) while the module denoted model generator operates in the preliminary stage of system implementation on a given circuit, processing the information received by the user about the particular structure of that circuit and providing this information in suitable form to the modules operating on line.

4 The Model Generator

The module which generates the model of the circuit involves three information flows: one in input and two in output [Diana et al. (1991)]. The input data are supplied directly by the user and consist of the topological description of the circuit and a list of parameters whose qualitative value may be obtained from the system via the acquisition module. The topological description consists of a list of the existing components, each of which characterized by a symbol which identifies its type and by the circuit nodes connected to it.

The model generator has essentially two functions. The first is to generate, for each quantity to be measured, a list of numerical values which constitute the thresholds that the acquisition module employs for discretizing the quantitative values measured. The threshold values, together with other information on the parameters concerned, represent the first flow of information in output which goes to the acquisition module. The second and more complex function is to construct the qualitative behavioral model of the circuit. Of the many existing possibilities, e.g., models in terms of differential or algebraic equations, numerical models, etc., we opted for a qualitative model of the circuit consisting of a set of relations (confluences) that relate the different quantities of interest (voltages, currents, and their first derivatives) in terms of
belonging to intervals such as

\[-\infty, -\epsilon[ \cup [\epsilon, +\infty[ \quad \epsilon > 0\]

rather than of precise values. The qualitative value of a quantity expresses which of the three intervals it belongs to. The confluences are expressed synthetically using a series of suitable qualitative operators (sum, product) that act on the qualitative variables [deKleer and Brown (1984)].

The choice between qualitative or quantitative approach is dictated essentially by the ability of the former to handle incomplete knowledge (i.e., circuits only partially known: this is frequently the case, given the tolerances with which the parameters of the different components are known), to handle equally well linear and nonlinear circuits and to focus the attention on the key aspects of the circuit, disregarding details of no significance in the diagnostic procedure [Cois et al. (1989)].

In the model generator the behavioral models of the most common electronic components have been implemented. They form a library, which may be built up if necessary, of general confluences describing the relations between the typical quantities of each component type. Six different types of confluences were employed:

1. **Equality to a constant**: expresses the condition that the indicated quantity is equal to a certain qualitative value.

2. **Equality**: expresses a relation of qualitative equality between two circuit quantities or more precisely a relation of implication between the two which holds in both senses: if the qualitative value of one of the two quantities is known, it is implied that the same value may be assigned to the other.

3. **Implication**: expresses a relation of implication in one sense only: i.e., it is a proper cause-effect relation. If the first of the two quantities has a certain qualitative value then also the second must have that same value.

4. **Conditioned implication**: expresses a unidirectional relation of implication that only holds provided the first quantity has a certain value, indicated in the confluence itself.

5. **Implication with three arguments**: allows the deduction of the value of the third quantity as the qualitative sum of the first two, whenever this sum does not lead to ambiguity. Actually the sum of two qualitative values is not always found.

6. **Zero sum**: expresses the event that the qualitative sum of three quantities is zero. In the simulation of the circuit behavior it is used for deducing the qualitative value of any one of the three quantities once the other two are known. However, this can be done only when the qualitative sum of the two known quantities is determinate; confluences of this type do not describe the behavior of a component but are derived from the two Kirchhoff laws.

The program examines each circuit component, extracts from the library the confluences relating to that type of component and details them. For example, for a resistor the library stores two general confluences, which express that the voltage at its terminals (and its derivative) and the current passing through it (and its derivatives) are qualitatively equal. If there is a resistor between nodes \(N_1\) and \(N_2\), two equality confluences are generated; one between the voltage \(V_{1,2}\) and the current \(I_{1,2}\) and the other between the derivatives of these variables. The component
in question is associated to each rule generated, to indicate that the relation only holds if the component is functioning properly.

In the case where a component can have a qualitatively different behavior depending on the state it is in at a certain instant (e.g., a diode that can operate in interdiction or in conduction), a specific operating model is constructed for each of the possible states. In such cases, the program details the confluences for all the possible states, and for each confluence generated indicates the state it corresponds to. For example, for a diode with terminals A and K, the following six rules are generated; the first two hold for the interdiction state, the others for the conduction state:

1. the current \( I_{A,K} \) is equal to zero;
2. the derivative of the current \( dI_{A,K} \) is equal to zero;
3. the voltage \( V_{A,K} \) is equal to the current \( I_{A,K} \);
4. conditioned implication between the derivative of the voltage \( dV_{A,K} \) and the derivative of the current \( dI_{A,K} \); the condition for activating the confluence is that \( dV_{A,K} \) is positive;
5. conditioned implication between the derivative of the voltage \( dV_{A,K} \) and the derivative of the current \( dI_{A,K} \); the condition for activating the confluence is that \( dV_{A,K} \) is negative;
6. conditioned implication between the derivative of the current \( dI_{A,K} \) and the derivative of the voltage \( dV_{A,K} \); the condition for activating the confluence is that \( dI_{A,K} \) is zero.

The last three confluences replace the confluence of equality between the variations in voltage and current that translate the theoretical qualitative relationship between the two. This was done because of the steep slope of the voltage–current characteristic of a diode in conduction owing to which a change in current may produce such an insignificant change in voltage that the system considers it qualitatively zero; conversely, even a minor change in voltage can produce a significant change in current.

The confluences of zero sum translate Kirchhoff’s laws into qualitative form. The program applies Kirchhoff’s voltage law as it visits the circuit components. For each bipolar component this law is applied to a set of three nodes composed of two terminals and the circuit ground, while, for components with more than two terminals, terns of nodes of interest are considered. Kirchhoff’s current law is then applied to the currents flowing into each circuit node.

The state of each component is determined by the diagnostic program, starting from the knowledge of the quantitative values of certain variables. However, this operation cannot always be done for all the components. It may then be useful to try to determine the state of the components also on the basis of the qualitative values obtained during the simulation of the circuit behavior. For this purpose the model generator generates rules for each component that may take different states: in these rules the qualitative values of one or two quantities and the state the component is in are indicated, if those quantities effectively take on those values.

Other rules are generated for certain components: each rule contains a combination of quantity values that could never arise were a certain component functioning properly, no matter what state it was in. These rules can therefore be used by the diagnostic module even when the state of the component has not been identified.

Once the list of confluences and rules that model the circuit has been generated, an optimization procedure is executed. This is necessary because some circuit quantities denoted in rules by
different pairs of nodes are actually the same. The set of generated confluences and rules, together with the circuit topology and list of parameters whose values can be obtained by the acquisition, comprises the flow of input data to the diagnostic module.

5 The Diagnostic Module

The diagnostic module is obviously the key element of the architecture. It comprises the conflicts detector and the candidates generator described in Section 2 and, basically, the simulator.

To perform the described diagnostic strategy, the system must be able to simulate the behavior of the circuit for different inputs on the basis of the qualitative model. It must also be able to justify the deduced value of each quantity of interest, i.e., to provide a list of all components whose correct behavior ensure that the deduction hold.

There are various qualitative simulation methods available: constraint centered [Knipers (1986)], process centered [Forbus (1984)], and component centered [deKleer (1984), deKleer and Brown (1984)]. We opted for the component centered approach, which is better suited for handling physical systems naturally consisting of component networks.

The approach followed is similar to deKleer and Brown (1984), but has two fundamental differences.

- In the simulation heuristics are not used, thus doing away with ambiguous deductions. This ensures that the system is correct, i.e., all the deductions are correct, at the expense of non exhaustivity, i.e., not all that may be physically determinable is made explicit.

- In the simulation of the system’s dynamic behavior, interstate simulation, i.e., the analysis of the qualitative behavior of the different quantities with time in deKleer’s terminology, is not done; on the contrary we proceed by successive intrastate simulations, analyzing the system through a series of “photographs” whereby the values of the quantities and their first derivatives are considered and each component is examined in the state in which the measurements indicate it to be in. This type of approach to simulation arises again from the need to safeguard the correctness of the conflicts determined, even at the cost of forsaking something. Interstate simulation is in fact essentially ambiguous in the sense that it gives rise to a number of possible developments which then have to be discriminated among, usually with heuristic considerations [deKleer (1984)].

The simulation algorithm can be reduced to the constraint propagation class but it is implemented with qualitative arithmetics which differ from the usual arithmetics for real numbers. The simulator achieves constraint propagation by making elementary deductions, each of which can be obtained as follows: given some observed or previously deduced quantities, find a quantity directly constrained by them, using the confluence that expresses the constraint. The procedure is repeated until no new deductions can be made. Generally it stops before values have been deduced for all the quantities of interest (non exhaustivity), basically because of the ambiguity of the qualitative arithmetics and because of feedback cycles present in each circuit.
6 Acquisition

Apart from reading the data and making the A/D conversion, the acquisition module also processes collected information [Fanni et al. (1992)]. This process consists essentially in making measurements discrete, i.e., passing from the numerical value provided by the acquisition board to the qualitative value to be fed to the diagnostic module proper (N/Q conversion). In the case at hand this value belongs to a set such as $[-, 0, +]$ depending on what interval the measurement falls into $]-\infty, -\epsilon[,$ $[-\epsilon, \epsilon[,$ $]\epsilon, +\infty[,$ (see section 4).

N/Q conversion is not a trivial operation because the different causes of uncertainty that may question the validity of the readings must be taken into account in order to avoid supplying inconsistent information to the diagnostic module.

The discrete values in output from the acquisition module, along with the qualitative model of the particular circuit, comprise the input to the diagnostic module.

6.1 N/Q Conversion

It is not simply a question of evaluating the sign of the measured quantities, because, often, other information has to be gleaned therefrom: for instance the state of the components in a given sampling instant. For certain measurements preprocessing is thus required and this consists in identifying which of the prefixed spaces, into which the real axis has been divided, they belong to.

To illustrate the above, take the example of the voltage measurements at the diode terminals as in Figure 3. The different discrete intervals on the real axis single out regions where a component behaves differently. These are not separated by a point but bands of uncertainty have to be introduced around the threshold values bounding them. This measure is required both because of the uncertainty in the measurements and because of the differences between components of the same type.

For the diode the threshold values are: $-\epsilon$ and $\epsilon$ around zero, the offset voltage and a sufficiently high value so that the diode cannot be considered to be functioning properly. If the measured value falls within a band of uncertainty, then some information has to be sacrificed. For instance, if the observed value falls within the interval of indetermination of the offset voltage, then the state of the diode cannot be determined but it can be ascertained that the voltage across its terminals is positive.

Bandwidth has been determined by means of tests on components of the same type and by means of statistical considerations on the scattering of the measurements around the actual value [Fanni et al. (1992)]. As for the width of the uncertainty bands around zero, they have been determined only on the basis of statistical considerations, being independent of component type.

Apart from the quantity values, the diagnostic module also uses the variations thereof, obtained as the difference between measurements in two successive sampling instances. These variations are viewed on a par with derivatives, assuming that readings are quick enough and second derivatives of the quantities sufficiently small. This simplification is possible owing to the qualitative approach adopted. In this case the conversion must take into account the combination of the uncertainties of the two measurements, and thus the width of the band of uncertainty is twice that of directly measured quantities.
The issue is further complicated when a quantity is obtained as the difference between two different measured quantities (for instance, the potential difference obtained from the measurements of two voltages referred to ground). Generally the two measured quantities are two random variables with different variance and the calculation of the width of uncertainty bands has, as a result, been modified.

Sometimes the uncertainty bands around zero overlap, thus including the zero value, and in this case a discrete nil value will never be obtained. Once again, in line with the philosophy of our implementation, we preferred to sacrifice some information rather than risk propagating ambiguous or incorrect data.

6.2 Non Simultaneity of Measurements

For each sampling interval, the acquisition board scans all the channels connected to the test points, usually more than one. We assume that if a quantity has the same qualitative value for two successive sampling instants, it keeps that value in the interval between them as well.

Clearly the measurements acquired on the different channels are not simultaneous, whereas the diagnostic module refers each series of measurements to a single mythical sampling instant. This gives rise to a number of problems which will be touched on only briefly. This problem is also discussed in DeCoste (1991).

Consider the example of Figure 4, which shows the qualitative trend of the two voltages $V_1$ and $V_2$ versus time. For simplicity, imagine that the quantities can only take two qualitative values + and −; the transition from + to −, or vice versa, can be viewed as the crossing of any threshold value. Obviously these considerations hold generally for the case of more than one threshold value.

Let $t_1, t_2, t_3$ denote the three time instants in which the voltage $V_1$ is read while $t'_1, t'_2, t'_3$ indicate the corresponding sampling instants for the voltage $V_2$. The latter values, as can be seen, are shifted with respect to the former by the same amount, equal to the delay due to reading the two respective acquisition channels. As can be observed, in the instant $t_2$ both quantities are positive but due to the delay the acquisition board reads the second as negative, as this quantity is acquired in the instant $t'_2$. Because the diagnostic module considers these measures referred to a single imaginary instant, the data to be processed would be incorrect, because they refer to two actual separate instants.

To solve this problem the series of values observed in both instants $t_2$ and $t'_2$ are considered, and for each instant only measurements of quantities that can be identified with certainty are taken into account. For instance, referring to the figure, in the instant $t_2$ the value of the voltage $V_1$ together with all the other quantities that have not changed qualitative value are considered, while the value of $V_2$ is undetermined. In $t'_2$ only the value of the voltage $V_2$ is maintained, while the value of $V_1$ is undetermined.

Even more complex situations may arise when more than two quantities change value simultaneously. Here a higher number of sampling instants than the actual ones has been considered and only the information known to be true for each mythical instant is kept. All the different cases handled have been solved with a suitable algorithm which is not described here, being outside the scope of the present investigation. This algorithms has been presented in Fanni et al. (1992).

Further problems arise when the quantities are determined as the difference between measured...
ones. These problems can be reduced by connecting the end nodes of an observable quantity to adjacent channels of the acquisition board or in any case to channels scanned by its multiplexer at instants as close as possible. However, here too, the strategy is to discard ambiguous or incorrect information.

7 Application Example

The efficiency of the ACDS system has been verified through a series of tests on the board depicted in Figure 5, which is part of a speed control circuit of a DC motor.

The board has been reconstructed to facilitate the simulation of different faults. However, we assumed that only a few test points are available for voltage measurement. These test points correspond to the physical terminals that may be accessed on the board and have been shown with a circle in Figure 5.

Nodes 18 and 52 are connected to a DC voltage generator; node 15 is connected to a voltage generator which has a direct component and a sinusoidal component with a frequency of 10 Hz; node 25 is not connected to any generator. \( O_1 \) and \( O_2 \) are two operational amplifiers, \( T_1 \) and \( T_2 \) are two trimmers, \( V_1 \) is a DC voltage generator. The bipolar components, such as resistors \( (R) \), diodes \( (D) \), capacitors \( (C) \), and double zener \( (Z) \), are denoted by the name of their terminals.

The measurements have been collected through an acquisition board with 32 channels in single-ended mode, i.e., the voltage of all test points are referred to a common ground. The sampling interval between two adjacent channels of the acquisition board is \( T = 200\mu s \). To show the influence of the sampling interval on the diagnosis, we have also reported the performance of the system with a sampling interval of \( T = 100\mu s \) (single fault table, test 2).

A first series of tests was carried out on the normally operating circuit to check that no faults were detected when the behavior of the system was correct. These tests were always successful: no candidates were proposed.

In the other series of tests, catastrophic circuit faults were simulated mainly in three ways:

- disconnecting one of the supplies of an operational amplifier or making it inoperative by feeding it with a exceedingly high voltage;
- disconnecting one terminal of a component;
- short-circuiting the end terminals of a component.

We simulated not only single faults, i.e., one component faulted at a time, but also multiple faults, i.e., two or more components faulted simultaneously.

Once the measurements acquired on a faulted circuit have been processed, the system proposes a series of minimal candidates; each candidate is a set of components, and may therefore comprise one or more components. Purely intuitive reasoning leads one to think of the single candidates, i.e., candidates consisting of one component, as the most likely culprits. In fact, the very definition of candidate means that such a component is present in all the conflicts identified. In general a test is considered successful when the faulted component figures among any one of the minimal candidates proposed.
It must be said that in all the tests on single faults that yielded successful results, the candidates proposed contained a single component. The system, however, rarely proposed just one candidate. Several components were always suggested as possible sources of fault; in other words a region of the circuit is delimited, generally fairly restricted, where the system has identified mismatches between values it expected.

The success and failure rates of tests are given below. These figures are not intended as statistics but merely summarize the results of fault simulations.

<table>
<thead>
<tr>
<th></th>
<th>( N_1 )</th>
<th>( N_2 )</th>
<th>( N_3 )</th>
<th>( N_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faults detected</td>
<td>26</td>
<td>31</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>without false alarms</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>with false alarms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faults likely detected</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>without false alarms</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>with false alarms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faults not detected</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>00</td>
</tr>
<tr>
<td>without false alarms</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>with false alarms</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 1: Examples of single fault tests.

In the tests with single faults, the fault was detected in 60% of the cases while in the remaining 40% no candidate was proposed. The success rate of tests in which the component was short-circuited was 100%, whereas in cases where a terminal had been opened it dropped to 50%. Such a low percentage may be attributed to the ambiguity of the qualitative sum, which halts causal propagation when Kirchhoff’s law is applied to the currents flowing into the end nodes of the faulted components.

Tests simulating two simultaneously faulty components yielded similar results. In 45% of the cases both faults were detected; in 45% of the cases only one fault was detected; in 10% of the cases no fault was detected.

In particular, it was observed that when the two faulted components were topologically close, only one of the faults was detected, due to the fact that the effects of one of the faults may partially mask the effects of the other, making it difficult to identify them correctly. Besides, bearing in mind that the system usually pinpoints the region of the circuit where the fault has occurred, it is understandable that the simultaneous failure of two neighbouring components may be assimilated to a single fault.

Faults in two components not close to each other are usually identified correctly, in the sense that the system proposes candidates deriving from the combination of the two sets of conflicts for the two faults. However, the number of components existing in such a set of candidates may, understandably, be fairly large and the double candidate, i.e., the set of faulted components, is not always present.

In Table 1 we have reported some of tests for single faults. In Table 2 we have reported some of the tests for multiple faults. We discuss the results in the following notes.

(a) The system correctly determines the area of the circuit where the fault is located. Due to the lack of internal test points, the system is not able to resolve among a fault on the operational amplifier, on its input resistor, or on its output resistor.
<table>
<thead>
<tr>
<th>Faults</th>
<th>Candidates</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 open circuit on $R_{36,0}$</td>
<td>${R_{36,0}}$, ${O_1}$, ${R_{2,43}}$</td>
<td>(a) (h)</td>
</tr>
<tr>
<td>short-circuit on $Z_{3,0}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19 open circuit on $R_{36,0}$</td>
<td>${T_1}$, ${R_{30,31}}$</td>
<td>(i)</td>
</tr>
<tr>
<td>open circuit on $R_{1,19}$</td>
<td>${R_{1,19}}$</td>
<td></td>
</tr>
<tr>
<td>20 short-circuit on $D_{34,68}$</td>
<td>Cartesian product of the candidates found in test 6 and 16</td>
<td>(j)</td>
</tr>
<tr>
<td>open circuit on $R_{36,0}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 open circuit on $D_{61,4}$</td>
<td>${R_{36,0}}$, ${O_1}$, ${R_{2,43}}$</td>
<td>(a) (k)</td>
</tr>
<tr>
<td>open circuit on $R_{36,0}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 open circuit on $R_{2,43}$</td>
<td>${O_1}$, ${R_{36,0}}$, ${R_{2,43}}$</td>
<td>(a)</td>
</tr>
<tr>
<td>open circuit on $R_{36,0}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 $O_2$ non operative</td>
<td>${O_1}$, ${R_{36,0}}$, ${R_{2,43}}$</td>
<td>(a) (c)</td>
</tr>
<tr>
<td>open circuit on $R_{36,0}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 open circuit on $R_{36,0}$</td>
<td>${O_1}$, ${R_{36,0}}$,</td>
<td></td>
</tr>
<tr>
<td>open circuit on $Z_{3,0}$</td>
<td>${R_{2,43}}$, ${Z_{3,0}, C_{39,40}, R_{39,41}, T_2}$</td>
<td></td>
</tr>
<tr>
<td>25 $O_1$ non operative</td>
<td>Cartesian product of the candidates found in test 3 and 9</td>
<td>(a) (j)</td>
</tr>
<tr>
<td>open circuit on $R_{22,13}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Examples of multiple fault tests.

(b) By increasing the sampling frequency of the acquisition board, we derive more information than in test 1. Under a single fault hypothesis, we may rule out a malfunctioning of $R_{2,43}$ that by itself does not explain the observed symptoms.

(c) Since node 25 is not connected to a supply, in normal operating conditions the current in $R_{5,6}$ is very low, being equal to the feedback current of $O_2$. Thus, a fault on $O_2$ may not be regarded as catastrophic. However, an open circuit on $R_{5,6}$ is detected by the system, since it has the effect of opening the feedback circuit.

(d) The system correctly determines the area of the circuit where the fault is located. The symptoms observed may be caused, in reality, by the malfunctioning of any of the candidates proposed.

(e) The fault causes a variation of the feedback impedance that is not detected because of the limit of the qualitative simulation.

(f) The fault is not detected because of the ambiguity of the qualitative sum that expresses Kirchhoff’s current law in node 43.

(g) The fault is not detected because of the ambiguity of the qualitative sum that expresses Kirchhoff’s current law in the internal node of trimmer $T_2$.

(h) The fault on $Z_{3,0}$ is not detected because of the ambiguity of the qualitative sum that expresses Kirchhoff’s current law in node 3.

(i) The fault on $R_{36,0}$ is masked. However, if the detected fault on $T_1$ is removed, the system will be able to detect the fault on $R_{36,0}$ (see test 6).

(j) The system detects the union of the conflicts detected when simulating each fault singularly. Thus the diagnosis is given by the Cartesian product of the candidates found when each of the two faults is singularly simulated.

(k) The fault on $D_{61,4}$ is not detected because in the simulated operating condition the diod is off.
8 Conclusions

This paper discusses our work in the area of automated fault diagnosis in analog circuits. The ACDS system falls into the class of mixed mode expert systems integrating the shallow knowledge of a troubleshooting expert with the deep knowledge of the device in question.

The circuit model is automatically constructed from a library of elementary components (resistors, diodes etc.) modelled using a qualitative approach, and exploiting the knowledge of the circuit topology and the laws of electrotechnics, also formalized qualitatively. The qualitative model, along with the values of appropriate quantities measured on the actual circuit and suitably translated into qualitative data, form the input to the diagnostic module. By triggering a causal propagation mechanism, the diagnostic module analyzes the circuit behavior, compares it with the expected behavior (the measured quantities), and from the mismatches detected identifies the candidates, i.e., the set of components the system proposes as culprits of the failure.

In order to ascertain the validity of the implemented system a number of simulations were carried out and the results are shown for a particular circuit, part of the speed regulation system of a DC motor. It emerged from the results that, because of the intrinsic limits of the qualitative approach, the system is not always able to correctly identify the faulted component, and often only identifies the region of the circuit where the fault has occurred. In these cases, quantitative methods must necessarily be integrated into the system, which being applied to small portions of the circuit are efficient enough. In this regard, the possibility is being examined of modifying the circuit model by dividing it up into functional blocks, each described by qualitative relations between inputs and outputs. This would permit pinpointing the block that is malfunctioning more rapidly, and subsequently performing a more detailed diagnosis of just the portion responsible for the fault.

References


