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Soft Faults Diagnosis in Analog Circuits Using Optimization Inspired by Bat Behavior

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Abstract. Open-circuit or short-circuit faults, as well as faults in discrete parameters are the most used models in the simulation method before testing. As the response of an analog circuit to an input signal is continuous, failures in any specific circuit element may not characterize all possible component failures. There are three important features in diagnosing analog circuit faults: faulty component identification, faulty element value determination, and circuit tolerance restrictions. To solve this problem, a fault diagnosis method is proposed in this work using a bat-inspired algorithm, where the nonlinear equations of the circuit under test are used to calculate the circuit parameters. The fault diagnosis is transformed into an optimization problem. The bats represents the values of faulty components and applied to the transfer functions of accessible nodes. the objective is to minimize the difference between the responses obtained in the real circuit and the response simulated by the optimization process, identifying which circuit component has the potential to present the failure. The proposed methodology is capable of diagnosing simple faults and is proven with the Biquad Tow-Thomas Filter.

Palavras-chaves: Fault Diagnosis, Analog Circuits, Algorithm, Bat, Optimization

1 Introduction

Electronic equipment comprising electronic circuits is categorized into analog and digital circuits. According to one statistic, almost 80% of electronic circuits in equipment are digital, but about 80% of failures occur mainly in the analog parts Binu and Kariyappa [1]. Diagnosing faults in analog circuits is more difficult due to the basic characteristics of the circuits, such as non-linearity and tolerance in the components, inefficient fault models, inadequate accessible nodes and uncertainty in measurements.

The development of strategies to diagnose faults in analog circuits is a challenging task that has encouraged a good amount of research, due to the increasing number of applications of these circuits and the high cost of tests. Areas such as telecommunications and biomedical applications need good performance in high frequency, low noise and power applications, which can only be achieved using analog integrated circuits Albustani [2]. Fault detection is an iterative and time-consuming process, as the fault diagnosis strategy is dependent on the expertise and experience that engineers have with the circuit. In last decades, a good amount of research in fault diagnosis has focused on developing tools that facilitate Fenton et al. [3] tasks. While important progress has been made, these new technologies have not been widely accepted. This should motivate researchers to investigate other paradigms and develop new strategies for fault diagnosis. The objective of this work is to present a new methodology based on optimization to solve the problem of fault diagnosis.

The rest of this paper is divides into 7 sections. Section 2 presents some relevant works on fault diagnosis in analog circuits. In Section 3, concepts of Transfer Function and Circuit Analysis are presented, which will be used to transform fault problems in analog circuits into an optimization problem. Section 4 presents the algorithm used. Section 5 presents the objective function and constraints of the problem. Section 6 presents the circuit used to prove the effectiveness of the proposed solution and the testing methodology. In the 7 section, the results obtained are presented and analyzed. Section 8 presents the conclusions and future work.

2 Related Works

The intelligence approach is also called the data-driven fault diagnosis approach. It is categorized into transformation-based techniques, optimization-based techniques, machine learning techniques, hybrid techniques, and rule-based techniques Binu and Kariyappa [1].

In Zhou and Shi [4], a simple smooth fault diagnosis method for analog circuit with tolerance based on *Particle Swarm Optimization* (PSO) is proposed. The parameter deviation of the circuit elements is defined as the particle element. Incremental node voltage equations based on sensitivity analysis are constructed as constraints of a linear programming equation. By inducing the penalty coefficient, the LP equation is defined as the suitability function for the PSO program.

In Yang [5], identifying faulty parameters is vital for predicting the remaining lifetime of the circuit under test. Based on the circuit's transfer function, the measured fault response is used to inversely deduce the possible fault parameters. The Genetic Algorithm reduces the possible range of fault parameters within which all faults can generate the same measured response. Based on the component parameters and the transfer function, each individual has a simulated response. The objective is to find all possible individuals that minimize the difference between the simulated and measured failure response.

3 Diagnosis via Optimization

Diagnosing faults in analog electronic circuits can be transformed into Yang et al. [6] optimization problems. The nonlinear equations of the circuit under test can be used to calculate the parameters of the circuit components. The identification of faults is given by the comparison between the parameters of the estimated components and the normal values.

Circuit analysis studies the behavior of current passing through an electrical circuit, making it possible to verify the influence of each electronic component on the circuit response to an input signal. Proposed by Hayt et al. [7], the transfer function is defined as the ratio between the Laplace transform of the output and input of a given system when the initial conditions are null. In the analysis of single input and output analog electronic circuits, as proposed by Yang [8], the transfer function of a circuit is described as a function of the node to which the circuit is being analyzed and can be represented by the eq. (1):

$$h^{(t)}(s,p) = \frac{\dot{U}_{out}}{\dot{U}_{in}} = \frac{a_n(p)s^n + a_{n-1}(p)s^{n-1} + ... + a_0(p)}{b_m(p)s^m + b_{m-1}(p)s^{m-1} + ... + b_0(p)}, \quad (1)$$

where t represents the accessible node of the circuit, p corresponds to the admittance of the components possible to have failure, $\dot{U}_{out}$ is the function that defines the output node under analysis of the circuit and $\dot{U}_{in}$ is the input function, both in the Laplace domain, and $m \geq n$. In the frequency domain, where $s = jw$ is set, it is observed that the frequency response of the circuit is expressed in complex form. t being the number of nodes in the circuit to be analyzed, the frequency response is given by the data set, according to eq. (2):

$$h(p) = [h^{(1)}_{Re}(p), h^{(1)}_{Im}(p), ..., h^{(t)}_{Re}(p), h^{(t)}_{Im}(p)], \quad (2)$$

where the vector of $h(p)$ refers to the transfer functions of each node of the circuit under test and $h^{(t)}_{Re}$ and $h^{(t)}_{Im}$ represent , respectively, the real and imaginary parts of $h^{(t)}(p)$.

In circuit analysis using the transfer equation, it is common to analyze the impulse response of the circuit, since in the Laplace domain the input voltage has a unit value Hayt et al. [7]. Since $\dot{U}_{in} = 1$, the eq. (1) is now defined by the $H(s,p) = \dot{U}_{out}(s,p)$.

4 Optimization Inspired by Bat Behavior

The Bat Algorithm technique (*Bat Algorithm* - BA) was proposed by Yang [9] and was inspired by the echolocation behavior of micro bats. Bats use echolocation to sense distance and know the difference between food/prey and obstacles. They usually fly at random speed v_i and position x_i with a fixed minimum frequency f_{min}, varying the wavelength and loudness A_0 to look for prey. Although the volume may vary, the intensity is assumed to vary from a large A_0 to a low A_{min}.

The movement of bats is defined by updating the frequencies f_i, positions x_i and velocities v_i in a search space of D dimensions. The new frequency solutions are obtained through the eq. (3):

$$f_i = f_{min} + (f_{max} - f_{fmin})\beta, \quad (3)$$

Algorithm 1 BA Algorithm

Objective function $f(x), x = (x_1, ..., x_d)^T$
Initialize the bat population $x_i (i = 1, 2, ..., n)$ and v_i
Define pulse frequency f_i at x_i
Initialize pulse rates r_i and the loudness A_i
while $t <$ Max number of iterations **do**
  Generate new solutions by adjusting frequency, and updating velocities and locations/solutions [eq. (3) to eq. (4)]
  if $rand > r_i$ **then**
    Select a solution among the best solutions
    Generate a local solution around the selected best solution
  end if
  Generate a new solution by flying randomly
  if $rand < A_i$ & $f(x_i) < f(x^*)$ **then**
    Accept the new solutions
    Increase r_i and reduce A_i
  end if
  Rank the bats and find the current best x^*
end while
Post process results and visualization

where f_{min} is the minimum frequency value, f_{max} is the maximum frequency value and β is a random vector drawn from a uniform distribution and $\beta \in [0, 1]$. From the frequency update, the bats determine the new velocity value, in the time step t, from the eq. (4):

$$v_i^t = v_i^t + (x_i^t - x_{best})f_i, \tag{4}$$

where x_i is the current position of the micro bat, x_{best} is the current global best value, which is located after comparing all the best solutions among the bats. Once the bat's velocity is updated, the current position is updated, given by $x_i^t = x_i^{t-1} + v_i^t$, where x_i^{t-1} is the bat's previous position at the moment t and v_i^t is the updated velocity.

In local search, given the best solution among the current ones, a new solution is generated using a random walk, given by $x_i^t = x_i^{t-1} + \epsilon A^t$, where $\epsilon \in [-1, 1]$ is a random number, while $A^t =< A_i^t >$ is the average loudness of bats over time t.

In addition to these, the loudness A_0 and the pulse emission rate r_i must be updated as the iterations proceed. When the bat finds its prey, the sound intensity decreases as $A_i^{t+1} = \alpha A_i^t$, while the pulse emission rate increases as $r_i^{t+1} = A_i^0[1 - exp(-\gamma t)]$, where α and γ are constants and $0 < \alpha < 1$ and $\gamma > 0$.

5 Objective Function and Constraints

The objective function calculation model is given by eq. (5). Since this is an optimization problem, the objective is to find values of p such that the absolute difference between $\dot{U}_{out}(p)$ and M is minimum, that is:

$$\min_p E = ||\dot{U}_{out}(p) - M||, \tag{5}$$

where $\dot{U}_{out}(p)$ is the component of the objective function that is calculated by the proposed algorithm, and M is the component obtained through the circuit analysis software.

The proposed method is the implementation of BA in order to optimize the values of p (for $p \geq 0$) in order to satisfy the objective function. In this methodology, the search for failure in the component will be verified through the value obtained from the optimization (p), comparing with the operating range informed by the component manufacturer. For this experiment, the operating range of ±5% of the nominal value is used, according to eq. (6):

$$f_i = \begin{cases} 0, & 0,95 * p_i \leq p_i^* \leq 1,05 * p_i \\ 1, & p_i^* < 0,95 * p_i ou p_i^* > 1,05 * p_i, \end{cases} \tag{6}$$

where p_i refers to the ideal value of the analyzed component.

6 Case Study

This section presents the circuit used in the case study and the application of the methodology implemented to detect faults in the circuit. Figure 1 shows the circuit used in this case study. The *Tow-Thomas Biquad* is an active second-order filter based on the topology of two Yu et al. [10] integrators.

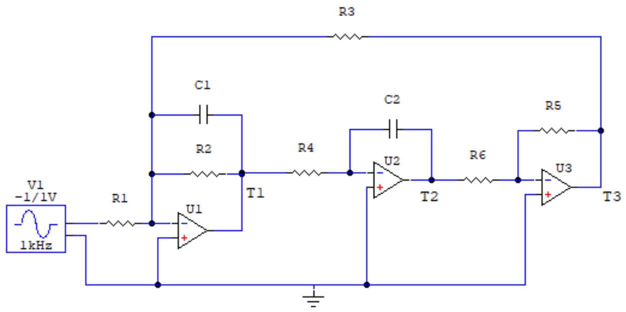

Figure 1. Biquad Tow-Thomas Filter

Through the circuit configuration, it is possible to adopt three accessible nodes, highlighted in Figure 1 as T_1, T_2 and T_3, whose transfer functions are:

$$h^{T_1}(jw) = \frac{-jw * R_2 * R_3 * R_4 * R_6 * C_2}{R_1 * R_2 * (R_5 - R_3 * R_4 * R_6 * C_1 * C_2 * w^2) + jw * R_1 * R_3 * R_4 * R_6 * C_2}, \tag{7}$$

$$h^{T_2}(jw) = \frac{R_2 * R_3 * R_6}{R_1 * R_2 * (R_5 - R_3 * R_4 * R_6 * C_1 * C_2 * w^2) + jw * R_1 * R_3 * R_4 * R_6 * C_2}, \tag{8}$$

$$h^{T_3}(jw) = \frac{R_2 * R_3 * R_5}{R_1 * R_2 * (R_5 - R_3 * R_4 * R_6 * C_1 * C_2 * w^2) + jw * R_1 * R_3 * R_4 * R_6 * C_2}, \tag{9}$$

In this case study, *software* are used to assist in the analysis of the circuit in obtaining the transfer function at the accessible nodes, minimizing the possibility of error, and in simulating the behavior of the circuit under test according to the change in the parameters of the components $p_i = [R_1, R_2, R_3, R_4, R_5, R_6, C_1, C_2]^T$, being possible to test it under different circumstances. For the circuit in Figure 1, 3 different cases are investigated:

- Case 1 – No faults: ideal parameters
- Case 2 – R_1 failed: R_1 with value of $4.32k\Omega$;
- Case 3 – R_4 failed: R_4 with value of $5.00k\Omega$.

BA is implemented in *Python*. The implementations carried out had fixed parameters in order to compare the results. The number of coordinates is equal to the number of components possible to fail. The parameters are initially defined with 8 dimensions, a population of 50 bats, alpha being 0.5, beta equal to 0.5, initial pulse of 0.1, minimum frequency of 0 and maximum of 5, and the space of search being the minimum of zero and maximum value being up to 20% greater than the ideal value of the component, according to eq. (10):

$$p_{i,initial} = 0, 0 \leq p_i \leq 1, 2 * p_{i,ideal}, \tag{10}$$

Components had default ideal values of $10k\Omega$ for Resistors and $10nF$ for Capacitors. In this configuration, the circuit behaves like a low-pass filter.

With the help of *Circuit Maker*™, the voltage values are measured in the accessible nodes of the circuit that will serve as a target for the implemented algorithm. The objective is for the implementation to obtain the best values of the circuit components so that the difference between the voltage values obtained by the implementation and the value measured by the *software* is minimal, minimizing the objective function describe in eq. (5). The measured values for each case defined in this study are presented in Table 1. The initial values of the components are randomly assigned, according to Table 2. Applying to eq. (7), eq. (8) and eq. (9), the *Python's* implementation will compare the values of functions using the values of the components with the values obtained through measurements at each accessible node on the circuit $U_{T_1} = (-0.007680 - j0.05475)$V, $U_{T_2} = (1.3130 - j0.1842)$V and $U_{T_3} = (0.8058 - j0.1131)$V.

The circuit nodes in Figure 1 are applied incrementally: individually, combined 2x2 and the three combined. In the first iteration of the implementation using the node T_1 individually, by eq. (5), the value of the objective

Table 1. Voltage measured at nodes T_1, T_2 and T_3.

	T_1 (V)	T_2 (V)	T_3 (V)
Case 1	-0.283-j0.451	0.717-j0.451	0.717-j0.451
Case 2	-0.655-j1.043	1.659-j1.043	1.659-j1.043
Case 3	-0.089-j0.286	0.910-j0.286	0.910-j0.286

Table 2. Initial values of the circuit components

Component	Value	Component	Value
R_1	1.156kΩ	R_5	6.816kΩ
R_2	4.601kΩ	R_6	11.107kΩ
R_3	9.501kΩ	C_1	0.852nF
R_4	6.347kΩ	C_2	1.045nF

function is $E_{T_1} = 0.4821$. Similarly for the nodes T_2 and T_3, individually, the objective function values are: $E_{T_2} = 0.6528$ and $E_{T_3} = 0.3489$.

Applying the 2x2 combined nodes, the calculation of the objective function by eq. (5) is given by eq. (11). So for the nodes T_1 and T_2 combined it is $E_{12} = 0.8115$. Similarly for the combinations of nodes T_1 and T_3, and T_2 and T_3 the values of the objective functions in the implementation are: $E_{13} = 0.7402$ and $E_{23} = 0.3489$.

$$E = \sqrt{||U_{T_1} - M_{T_1}||^2 + ||U_{T_2} - M_{T_2}||^2} \tag{11}$$

For the combination of the three nodes, the calculation of the objective function by eq. (5) is given by eq. (12). Therefore, the value of the objective function of the three nodes combined is $E_{123} = 0.8834$.

$$E = \sqrt{||U_{T_1} - M_{T_1}||^2 + ||U_{T_2} - M_{T_2}||^2 + ||U_{T_3} - M_{T_3}||^2} \tag{12}$$

At the end of the execution of the optimization process using the node T_1, the solution obtained is given in Table 3. It is verified that the values found are within the normal operating range of the components, according to eq. (6). With these parameters, the minimization of the values of the objective function for individual and combined nodes are observed, as shown in Table 4.

Table 3. Final values of the circuit components after optimization

Component	Value	Component	Value
R_1	10.020kΩ	R_5	9.975kΩ
R_2	10.023kΩ	R_6	9.968kΩ
R_3	10.015kΩ	C_1	9.985nF
R_4	10.019kΩ	C_2	10.004nF

Table 4. Objective function values for different studied cases

Nodes	Value	Node	Value	Node	Value
T_1	0.000471149	T_1/T_2	0.001331517	$T_1/T_2/T_3$	0.001497285
T_2	0.001245374	T_1/T_3	0.001421225		
T_3	0.00068478	T_2/T_3	0.00068478		

7 Performance Results

In this section, the results obtained through the execution of the proposed method will be presented. As described in Section 6, tables will be presented containing data with individual nodes (T_1, T_2 and T_3) and combined nodes (T_1 and T_2, T_1 and T_3, T_2 and T_3, and T_1, T_2 and T_3). For each case, 56 simulations are performed. In each of the 3 cases, a node or a combination of nodes from the Figure 1 circuit are used, restricting the analysis to one component. The parameter under analysis varies within the search space, according to eq. (10). The other components vary within the normal operating range, according to eq. (6). Each simulation ran the implementation 100 times, for a total of 16,800 runs. In this case study, in addition to *Circuit Maker*™, *software SapWin4*™was used. *SapWin4*™is a tool used to obtain the transfer function of accessible nodes in the circuit, minimizing the possibility of error for the manual calculation of functions. The Equations 7, 8 and 9 are obtained using this *software*.

7.1 Case 1: No faults

As described in Section 6, Case 1 has the components parameters within the operating range. Table 5 presents the results obtained using the nodes T_1, T_2 and T_3 individually, and the results obtained from the optimization with the combined nodes T_1 and T_2, T_1 and T_3, and T_2 and T_3. It is observed that, using the node T_1, 70% of the executions presented the result without failure when the component C_1 was analyzed (S_{C_1}), while using T_2 and T_3 had 82% and 90% flawless results, respectively. Therefore, using the T_3 node performed better. When the other components are analyzed, the performance was higher than 84% using node T_1, 89% using node T_2 and 90% using node T_3. Using the combination of nodes T_1 and T_2, analyzing the capacitor C_1, there was a hit rate of 87%, the same performance of the analysis when using the node T_2 and T_3 As for the combination of nodes T_1 and T_3, there was a 90% hit rate. However, when analyzing the other components, there was a better performance in the method with a hit rate above 93% for the combination of nodes T_1 and T_2, with a hit rate of 90% for the combination of nodes T_1 and T_3, and 95% for the combination of nodes T_2 and T_3.

Table 5. Results of Case 1 referring to the nodes individually and combined 2x2.

	T_1 / T_2 / T_3								T_1 e T_2 / T_1 e T_3 / T_2 e T_3							
	S_{R_1}	S_{R_2}	S_{R_3}	S_{R_4}	S_{R_5}	S_{R_6}	S_{C_1}	S_{C_2}	S_{R_1}	S_{R_2}	S_{R_3}	S_{R_4}	S_{R_5}	S_{R_6}	S_{C_1}	S_{C_2}
NF	99/96/99	100/91/90	87/100/100	84/100/90	90/95/100	92/95/89	70/82/90	90/89/95	100/100/100	100/100/96	97/100/100	98/97/95	95/90/95	93/92/100	87/90/87	100/95/95
R_1	1/4/1	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
R_2	0/0/0	0/9/10	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/4	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
R_3	0/0/0	0/0/0	13/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	3/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
R_4	0/0/0	0/0/0	0/0/0	16/0/10	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	2/3/5	0/0/0	0/0/0	0/0/0	0/0/0
R_5	0/0/0	0/0/0	0/0/0	0/0/0	10/5/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	5/10/5	0/0/0	0/0/0	0/0/0
R_6	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	8/5/11	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	7/8/0	0/0/0	0/0/0
C_1	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	30/18/10	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	13/10/13	0/0/0
C_2	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	10/11/5	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/5/5

Table 6 shows the results obtained regarding the use of the three nodes in the optimization. It is observed that using the three nodes combined, there is a better performance of the model, as the hit rate increased from 66% to 71% when the Capacitor C_1 is analyzed, and it is higher than 94% in the other components.

Table 6. Results of Case 1 referring to the three nodes combined.

	T_1, T_2 e T_3							
	S_{R_1}	S_{R_2}	S_{R_3}	S_{R_4}	S_{R_5}	S_{R_6}	S_{C_1}	S_{C_2}
SF	100	98	99	98	100	95	91	95
R_1	0	0	0	0	0	0	0	0
R_2	0	2	0	0	0	0	0	0
R_3	0	0	1	0	0	0	0	0
R_4	0	0	0	2	0	0	0	0
R_5	0	0	0	0	0	0	0	0
R_6	0	0	0	0	0	5	0	0
C_1	0	0	0	0	0	0	9	0
C_2	0	0	0	0	0	0	0	5

In the case without failures, it is observed that the greater the number of nodes used, the better the performance of the method. Therefore, using the nodes T_1, T_2 and T_3 combined, there was the best performance of the method, according to Table 6.

7.2 Case 2: Failure in R_1

As described in Section 6, Case 2 has the value of R_1 equal to $4.32k\Omega$ and other components within the operating range. For the case with failure, it is observed that when a component is analyzed that does not correspond to the one with the failure, the method presents failures in more than one component. Table 7 presents the results obtained using the nodes T_1, T_2 and T_3 individually, and the results obtained from the optimization with the combined nodes T_1 and T_2, T_1 and T_3, and T_2 and T_3. It is observed that using the nodes individually or combined 2x2, the component R_1 presents an isolated failure in this resistor. In the other analyzed components, there is more than one component with simultaneous failure.

Table 7. Results of Case 2 referring to the nodes individually and combined 2x2.

	T_1 / T_2 / T_3							
	S_{R_1}	S_{R_2}	S_{R_3}	S_{R_4}	S_{R_5}	S_{R_6}	S_{C_1}	S_{C_2}
NF	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
R_1	100/100/100	73/90/93	89/87/84	82/91/91	84/90/93	83/82/94	84/92/91	83/93/95
R_2	0/0/0	94/94/90	82/86/79	72/89/86	74/87/86	73/90/85	75/90/89	73/92/87
R_3	0/0/0	61/82/70	83/86/82	73/87/72	74/84/80	76/80/74	74/87/73	73/85/84
R_4	0/0/0	59/83/85	79/84/80	88/88/91	74/80/77	72/88/79	72/82/84	71/90/85
R_5	0/0/0	73/89/88	87/92/75	80/92/87	95/91/94	80/94/87	81/92/83	82/93/88
R_6	0/0/0	61/81/87	78/80/75	78/84/83	71/78/87	85/85/93	78/78/86	76/85/84
C_1	0/0/0	68/86/86	79/84/75	74/90/83	79/82/86	76/85/88	89/89/93	73/86/87
C_2	0/0/0	63/81/81	76/84/70	73/93/85	76/84/83	76/81/82	75/82/83	85/87/88

	T_1 e T_2 / T_1 e T_3 / T_2 e T_3							
	S_{R_1}	S_{R_2}	S_{R_3}	S_{R_4}	S_{R_5}	S_{R_6}	S_{C_1}	S_{C_2}
NF	0/0/0	0/0/0	0/0/0	8/16/0	0/11/0	0/11/0	0/0/0	4/11/0
R_1	100/100/100	75/79/77	80/68/78	78/77/75	72/83/81	72/84/82	77/86/78	85/82/84
R_2	0/0/0	85/92/96	68/62/76	75/65/69	64/74/77	68/74/78	75/79/76	71/75/78
R_3	0/0/0	69/72/63	87/92/88	75/64/61	65/70/68	61/71/69	68/75/61	79/68/68
R_4	0/0/0	64/67/66	72/58/68	76/73/87	64/73/74	59/74/71	71/74/64	74/72/72
R_5	0/0/0	75/72/69	78/63/71	74/71/73	99/71/96	69/81/79	78/83/73	82/78/80
R_6	0/0/0	65/65/67	75/57/70	76/72/69	64/72/76	87/82/91	74/75/72	80/73/75
C_1	0/0/0	70/72/71	80/62/72	79/71/73	66/71/78	67/76/76	88/91/92	83/68/78
C_2	0/0/0	61/71/63	67/61/72	70/59/69	61/59/70	59/72/71	66/75/73	80/78/91

Table 8 presents the results obtained regarding the use of the three nodes in the optimization. It can be seen that, using the three nodes combined, Resistor R_1 had 100% failure when analyzed. From the obtained results, it is possible to observe that in any of the nodes used, individually or in their combinations, we obtained that 100% of the executions presented a failure in the isolated component R_1.

Table 8. Results of Case 2 referring to the three nodes combined.

	T_1, T_2 e T_3							
	S_{R_1}	S_{R_2}	S_{R_3}	S_{R_4}	S_{R_5}	S_{R_6}	S_{C_1}	S_{C_2}
NF	0	0	0	7	0	1	0	3
R_1	100	63	71	74	77	74	77	83
R_2	0	97	68	68	72	68	69	75
R_3	0	56	79	60	65	60	62	68
R_4	0	58	61	81	63	63	65	70
R_5	0	57	63	69	94	68	74	79
R_6	0	54	58	63	70	93	67	77
C_1	0	57	65	66	71	66	94	80
C_2	0	54	64	62	67	61	64	80

7.3 Case 3: Failure in R_4

As described in Section 6, Case 3 has the value of R_4 equal to $5.0k\Omega$ and other components within the operating range. Table 9 presents the results obtained using the nodes T_1, T_2 and T_3 individually, and the results obtained from the optimization with the combined nodes T_1 and T_2, T_1 and T_3, and T_2 and T_3. It is observed that, using the node T_1, the components R_4, R_6 and C_2 had 100% failure when analyzed. Using node T_2, components R_4 and C_2 had 100% failure when analyzed. Using node T_3, components R_4, R_6 and C_2 had 100% failure when analyzed. Using the combination of nodes T_1 and T_2, components R_4 and C_2 had 100% failure when analyzed. Using the combination of nodes T_1 and T_3, components R_4, R_6 and C_1 had 100% failure when analyzed. Using the combination of nodes T_2 and T_3, components R_4 and C_2 had 100% failure when analyzed.

Table 9. Results of Case 3 referring to the nodes individually and combined 2x2.

	T_1 / T_2 / T_3							
	S_{R_1}	S_{R_2}	S_{R_3}	S_{R_4}	S_{R_5}	S_{R_6}	S_{C_1}	S_{C_2}
NF	0/10/3	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
R_1	94/78/79	91/58/68	0/70/76	0/0/0	89/67/59	0/63/0	87/77/71	0/0/0
R_2	89/75/85	84/95/92	0/73/76	0/0/0	90/67/63	0/71/0	84/86/78	0/0/0
R_3	88/72/82	88/60/70	100/88/85	0/0/0	90/68/57	0/62/0	84/74/69	0/0/0
R_4	87/68/84	90/56/69	0/69/75	100/100/100	91/68/63	0/61/0	82/82/79	0/0/0
R_5	94/74/88	94/56/70	0/72/77	0/0/0	93/94/98	0/68/0	83/81/77	0/0/0
R_6	89/74/90	89/57/68	0/70/70	0/0/0	94/67/62	100/91/100	86/80/75	0/0/0
C_1	87/70/90	95/62/72	0/72/76	0/0/0	94/72/67	0/67/0	91/93/97	0/0/0
C_2	92/75/87	89/54/75	0/72/73	0/0/0	94/63/63	0/66/0	83/81/74	100/100/100

	T_1 e T_2 / T_1 e T_3 / T_2 e T_3							
	S_{R_1}	S_{R_2}	S_{R_3}	S_{R_4}	S_{R_5}	S_{R_6}	S_{C_1}	S_{C_2}
NF	2/1/30	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
R_1	88/90/61	74/91/26	70/62/36	0/0/0	72/65/34	77/0/45	65/62/38	0/0/0
R_2	92/84/60	85/88/100	62/58/51	0/0/0	78/61/41	74/0/47	71/60/40	0/0/0
R_3	79/88/54	77/80/32	87/93/91	0/0/0	73/56/39	74/0/43	71/64/39	0/0/0
R_4	93/88/56	78/84/34	69/64/40	100/100/100	78/65/37	76/0/48	72/60/40	0/0/0
R_5	84/93/59	82/89/27	71/66/41	0/0/0	90/94/93	73/0/42	70/67/39	0/0/0
R_6	86/92/58	72/86/33	66/60/39	0/0/0	78/63/37	92/100/95	70/64/41	0/0/0
C_1	89/90/61	79/88/31	71/65/41	0/0/0	80/63/35	77/0/45	95/95/98	0/0/0
C_2	86/90/61	84/88/34	73/62/40	0/0/0	78/61/41	74/0/46	67/68/42	100/100/100

Table 10 presents the results obtained regarding the use of the three nodes in the optimization. It is observed that the analysis of the components R_4 and C_2 had 100% failure.

Table 10. Results of Case 3 referring to the three nodes combined.

	T_1, T_2 e T_3							
	S_{R_1}	S_{R_2}	S_{R_3}	S_{R_4}	S_{R_5}	S_{R_6}	S_{C_1}	S_{C_2}
NF	16	0	0	0	0	0	0	0
R_1	77	39	47	0	38	30	47	0
R_2	69	96	45	0	38	30	50	0
R_3	59	47	99	0	33	29	46	0
R_4	65	44	48	100	39	34	51	0
R_5	64	48	43	0	96	31	48	0
R_6	65	45	42	0	38	95	45	0
C_1	72	45	44	0	39	30	95	0
C_2	67	49	43	0	37	29	50	100

Although the proposed method did not identify the specific failing component, the algorithm was able to reduce the number of possible components to fail from eight to two components.

8 Conclusion

Developing test strategies to detect and diagnose faults in analog and mixed-signal circuits is a challenging task. In the field of diagnosing faults in analog circuits, there are three important characteristics: identification of the faulty component, determination of the value with faulty component, and circuit tolerance restrictions.

In this work, BA is used as an optimization technique to find the best solution of the circuit components for the transfer functions obtained in the accessible nodes and compared with the values measured by simulation. When comparing the values obtained from the optimization with the nominal value, there is a check if the component is in the tolerance range and determination if it has failure or not. Although some cases studied in this work do not have the specific result of identifying the component, there is a reduction in the number of possible components with failures, which shows that the proposed method has the capacity to help in the identification of the failed component. The results obtained show the feasibility of the proposed method.

For the case study, the methodology reduced the number of possible components to fail by up to 75% or identified the failing component. It is also observed that the optimizations that used the node T_3, using it individually or in combination, had a better performance in relation to the other accessible nodes of the circuit.

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