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Soft fault diagnosis in analogue circuits based on the Pearson correlation

***Abstract**. The paper deals with the diagnostic algorithm for soft faults in analogue circuits. It bases on the spectrum analysis of the circuit response to the rectangular input signal. The classifier applied in the location uses Pearson correlation coefficient. The identification is based on the formulas constructed with use of the evolutionary method: gene expression programming. The algorithm represents SBT (Simulation Before Test) technique and requires multiple analysis of circuit under test for building a fault dictionary. The numerical example shows the effectiveness of the algorithm.*

Streszczenie.** W artykule przedstawiony został algorytm diagnozowania parametrycznych uszkodzeń układów analogowych. Bazuje on na analizie FFT odpowiedzi badanego układu na prostokątny sygnał wejściowy oraz stosuje jako klasyfikator współczynnik korelacji Pearsona. Algorytm reprezentuje technikę SBT i wymaga wielokrotnych analiz badanego układu pozwalających na zbudowanie słownika uszkodzeń. Przedstawiony przykład obliczeniowy potwierdza efektywność algorytmu. (**Diagnostyka uszkodzeń parametrycznych z wykorzystaniem korelacji Pearsona).

Keywords:, soft fault diagnosis, dictionary diagnostic methods, correlation, parameter tolerance
Słowa kluczowe: diagnostyka uszkodzeń parametrycznych, metody słownikowe, korelacja, tolerancja parametrów

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Introduction

The fault diagnosis of the analogue circuits is the area of great importance in the process of design, manufacturing and utilisation of electronic devices. Despite the over thirty years of the research development [1-9], there is still a need of new universal, quick and effective, diagnostic methods. There are two main causes of such a situation. The first one is the difficulty of diagnosing the analogue circuits, due to the non-linear characteristics and tolerances of the system's elements. The second - new challenges, like limited access to the systems' interiors.

The challenges appearing before the modern diagnostics of analogue circuits are, apart from the before-mentioned limited access to systems' interiors, the high speed of diagnostic methods used during the production process, effectiveness and accuracy enforced by the increasing demand for reliability of finished products, and more frequently occuring global failures, which are the effect of the production process of electronic systems.

The proposed algorithm includes some of the above-mentioned requirements: for measurements, it uses only the output of the CUT (Circuit Under Test), and it belongs to the group of SBT methods, which are known for not being time-consuming.

Basic information about the algorithm

The method constructed for circuits with limited access to the systems' interiors use often the analysis in frequency domain. It enables to supply the sufficient number of test points through increasing the number of calculated harmonics [1-2,10]. The precision of measurement instruments and the magnitude of harmonics determine in this case the upper limit of test points.

Method described below has much in common with the one's proposed in [11-12]. The basis of all these methods is the frequency analysis of CUT. The important difference between the proposed in this paper algorithm and the one presented in [11] is the kind of classifier used in the process of fault localization. The algorithm presented below and the one described in [12] use the same classifier and the significant difference is the type of faults. The method presented in this paper is dedicated to the localization and identification of the parametric fault in the dynamic analogue circuits. The minimum of knowledge about CUT:

- the scheme of the circuit's connections and the nominal values of its parameters must be known; this enables the pre-test analyses for any parameters' values, enabling us to construct the fault dictionary,
- the maximum multiplication of the fault is determined.

The values measured in the proposed method are the harmonic signals measured in the available nodes of the diagnosed circuit. In the example described in the paper, it is one node – the output of the circuit. The effectiveness of the method is determined by the magnitude of changes of the output signal in the faulty CUT. To minimize the time consumption of the analysis, the excitation is considered to be the rectangular signal, which ensures the minimum drop of the average value resulting from the increase of the order of harmonic. This allows a sufficiently accurate measurement of maximum number of harmonics of the analyzed signal. The analysis of harmonics is beneficial for two reasons: it allows the increase of the number of measured values (higher number of measurement points), and is easily realizable in practice by the use of commercially available in measurement instruments function of FFT (Fast Fourier Transform).

Classifier construction of the proposed method is based on Pearson's correlation coefficient calculated for the relative changes in harmonic output of the analysed circuit. The Pearson correlation coefficient is a value indicating the level of the linear dependence of certain variables, such as *x* and *y*. Let *x* and *y* represent some random values of both variables (i = 1,2, ..., n). The Pearson correlation coefficient P_{xy} defines the relationship:

(1) $$P_{xy} = \frac{\sum_{i=1}^{i=n}\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{i=n}\left(x_i - \bar{x}\right)^2}\sqrt{\sum_{i=1}^{i=n}\left(y_i - \bar{y}\right)^2}}$$

where:

(2) $$\bar{x} = \frac{1}{n}\sum_{i=1}^{i=n} x_i$$

and

(3) $$\bar{y} = \frac{1}{n}\sum_{i=1}^{i=n} y_i$$

are the arithmetic means of the variables *x* and *y*.

Range of the Pearson correlation coefficient is [-1, 1]. Its values define the relationship between two quantities, which are arguments in the formula (1). The larger the absolute value of the ratio, the stronger the linear relationship between the variables. When $P_{xy} \to 0$ there is no linear relationship between the variables x and y. $P_{xy} \rightarrow 1$ and $P_{xy} \rightarrow -1$ indicate a strong interdependence of the variables x and y, but in the latter case the trends are opposite.

The samples of signals are the values of relative changes in zero harmonic, and odd harmonic orders of the output signal of the analyzed circuit.

(4) $$\delta A^{(i)} = \frac{A^{(i)} - A^{(i)}_{nom}}{A^{(i)}_{nom}}$$

where: $\delta A^{(i)}$ denotes the relative change of the harmonic of i^{th} order, $A^{(i)}$ is the actual value of the amplitude of the i^{th} voltage harmonic, $A^{(i)}_{nom}$ is the value of the i-th voltage harmonic in the unfaulty circuit. The measured values of the circuit can be the amplitudes or average values. They can be determined on the basis of FFT analysis of the diagnosed signal, the execution of which is allowed by the most of the available oscilloscopes. In the constructed dictionary, reference vectors are provided for each malfunction, which in the example described below, consist of nine elements:

(5) $$S = \left[\delta A^{(0)}, \delta A^{(1)}, \delta A^{(3)}, \delta A^{(5)}, \delta A^{(7)}, \delta A^{(9)}, \delta A^{(11)}, \delta A^{(13)}, \delta A^{(15)}\right]$$

These vectors correspond to a selected value of a parametric failure belonging to the range provided for the diagnosis of damage. In the example described below they are the values corresponding to ± 25% of change in the value of the damaged element. This value should be chosen experimentally. As a rule, it corresponds to half of the range provided for the diagnosis of parametric failures. Localization of the damage involves the determination of the correlation coefficient P of vector S_{akt} defined for the test voltage of the damaged circuit and all reference vectors S_{wz} corresponding to the damages of those components, the possibility of which has been provided. Each S_{wz} vector is associated with a different signature from a damage dictionary. After listing all correlation coefficients (6) the location of damage is specified. This corresponds to the highest value of the correlation coefficient.

(6) $$P_{S_{akt}S_{wz}} = \frac{\sum\limits_{i \in I}\left(\delta A^{(i)}_{akt} - \overline{\delta A_{akt}}\right)\left(\delta A^{(i)}_{wz} - \overline{\delta A_{wz}}\right)}{\sqrt{\sum\limits_{i \in I}\left(\delta A^{(i)}_{akt} - \overline{\delta A_{akt}}\right)^2}\sqrt{\sum\limits_{i \in I}\left(\delta A^{(i)}_{wz} - \overline{\delta A_{wz}}\right)^2}}$$

where:

(7) $$I = [0,1,3,5,7,9,11,13,15]$$

The highest correlation coefficient determined (6) is generally different from 1, due to the fact that the damage to the target value is different from the value adopted for the pattern, and due to the possible deviation of the undamaged parts of the nominal value according to the tolerance of the elements.

Signatures of the constructed damage dictionary contain not only model vectors (5), which are constructed from the relative changes in output harmonic, functions for identifying damage. They are appointed by the heuristic method of gene expression programming. Its operation is explained, inter alia, in [13-15]. These expressions are defined for systems with nominal values of undamaged circuits. Values of the damage defined with their may differ from actual due to non-zero values of tolerance parts.

The example of the algorithm's use

The following is an example of diagnostic analysis representing an illustration of the method described in chapter 2. Circuit shown in Figure 1, taken from [16] belongs to the so-called benchmarks. The analyses are performed with PSpice and Matlab.

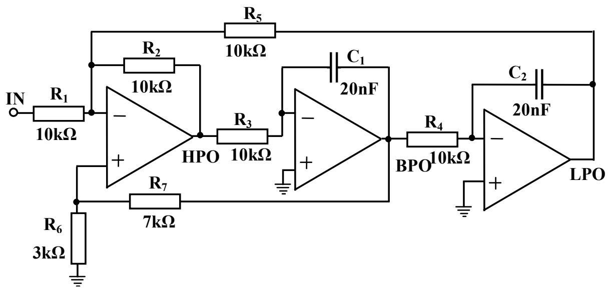

Fig.1. The benchmark circuit analysed in the paper

The circuit is a filter with three outputs: HPO is a filter output leaking out high frequencies, the output bandpass BPO, LPO is a low-pass filter output. Nominal values of the parameters of the elements are given in the figure. Stimulation of the circuit was a rectangular signal with positive values and amplitude of 5V. The single parametric damage of all resistors and capacitors with values of damaged parts falling within the limits of ± 10% to ± 40% of nominal resistance or capacitance, respectively, were provided for. The analysed signal was the voltage signal at the output of LPO, or more specifically the DC component and odd harmonics from the first to the fifteenth.

The construction of the dictionary serving fault localization, is based on the calculative appointment of vectors (5) for the nominal circuit and all circuits with pattern values of faulty elements, i.e. +25% and -25% for each resistor and a capacitor. This involves the analysis of 19 different circuits together, and allows to specify 19 dictionary entries.

Table 1. Pearson correlation coefficients for R_2 = 0,75 R_{2nom}

Size of fault	Potentially faulty elements				
	C_1	C_2	R_1	R_2	R_3
-40%	-0.8295	-0.9790	0.4342	0.9920	-0.8275
-35%	-0.8433	-0.9860	0.4219	0.9966	-0.8431
-30%	-0.8598	-0.9897	0.4150	0.9992	-0.8591
-25%	-0.8738	-0.9908	0.4470	1.0000	-0.8746
-20%	-0.8854	-0.9907	0.3963	0.9993	-0.8854
-15%	-0.9002	-0.9864	0.3996	0.9973	-0.8987
-10%	-0.9111	-0.9830	0.4743	0.9945	-0.9109
10%	0.9447	0.9597	-0.3686	-0.9786	0.9457
15%	0.9504	0.9581	-0.4622	-0.9720	0.9508
20%	0.9578	0.9489	-0.4039	-0.9649	0.9578
25%	0.9622	0.9428	-0.4616	-0.9578	0.9626
30%	0.9675	0.9351	-0.4294	-0.9532	0.9675
35%	0.9711	0.9309	-0.4370	-0.9481	0.9710
40%	0.9743	0.9227	-0.4445	-0.9414	0.9744

Size of fault	Potentially faulty elements			
	R_4	R_5	R_6	R_7
-40%	-0.9790	-0.9579	-0.3679	0.4595
-35%	-0.9859	-0.9692	-0.3844	0.4586
-30%	-0.9897	-0.9779	-0.3901	0.4477
-25%	-0.9912	-0.9847	-0.3864	0.4475
-20%	-0.9902	-0.9897	-0.3640	0.4263
-15%	-0.9884	-0.9931	-0.4312	0.4150
-10%	-0.9841	-0.9952	-0.4736	0.3726
10%	0.9597	0.9928	0.3903	-0.4725
15%	0.9565	0.9911	0.4285	-0.4248
20%	0.9506	0.9875	0.4387	-0.4220
25%	0.9416	0.9845	0.4433	-0.3827
30%	0.9353	0.9810	0.4398	-0.4131
35%	0.9286	0.9772	0.4549	-0.3932
40%	0.9222	0.9734	0.4446	-0.3817

To illustrate the possibility of fault localization, Pearson correlation coefficients for each damage pattern, an unfaulty circuit and circuits with damaged elements have been defined, the parameters of which differ from the nominal value at ± 10%, ± 15%, ± 20%, ± 25% , ± 30%, ± 35% and ± 40%. Below in Table 1 are listed the values of calculated Pearson correlation coefficients for the reference value of the defective part R_2 = 0.75 • R_{2nom} or δR_2 = -25% and all other damaged parts. The presented table shows that the highest correlation coefficient values are for the reduced values of the element R_2. Related correlations, values above 0.99, are there only for 10% and 15% increase of R_5. But this does not mean the ideal localization result in case of case of extending the resistance of element R_2 in the range of ± 10% to ± 40%.

Allowed tolerances change the correlation value, even though the change of correlation value in percents is not equal to the tolerance value specified as a percentage.

The analysis of tables containing tolerance values set for anything other than the R_2 leads to the conclusion that ambiguities are identified in the circuit under study. That group includes such elements as C_2 and R_4. The effects caused by the same changes in the value of these elements are the same, both at the decrease of the resistance and capacitance, as well as at changes in the opposite direction. Another group of ambiguities are the elements R_1, R_6 and R_7, wherein R_6 parameter changes work in the opposite direction to the changes of the other two components: R_1 and R_7.

In order to verify the effectiveness of the method and the above predictions of its operations, 90 localization attempts of failed components has been made – 10 damages of each element. The value of damage was determined randomly, as well as the current values of non-defective elements, localized within the tolerance limits established for all elements at 2%. The resulting locations were correct in 89%.

For the identification of the damage, the gene expression programming was used, allowing for the determination of function expressions. In the proposed diagnostic method, those function expressions, determine the value of the defective element on the basis of one or more harmonics of a signal. This algorithm has been described by its author in [13]. Its use for diagnostic purposes is described in [14] and [15]. The algorithm does not take into account the tolerance of the elements intact, which undoubtedly affects the accuracy of the identification process. In the example discussed, for the determination of changes in the value of R_2, the expression was determined:

$$\begin{aligned}&\mathbf{CECaa/aaaaaaa - a - {+}Eaaaaaaa - + - +}\\&\mathbf{Saaaaaaa + {-}aLSCaaaaaaa - C + {-}C + aaaaa}\end{aligned} \quad (8)$$

which after decoding gives the function (9):

$$\begin{aligned}\delta R_2 &= \cos(\exp(\cos(a))) + \exp(a) - 8a - 2\sin(a) +\\&+ \ln(\cos(a)) + 1 - \cos(a)\end{aligned} \quad (9)$$

where: δR_2 is the relative change of R_2 , variable a is relative change of the third harmonic, determined from measurements

Remarks and conclusions

The analysis of the algorithm presented in this paper and its performance in case of the filter confirm the good efficiency of the method. A new element is the use of correlation in the location of the damage. The advantage of the proposed classifier is its simplicity and the short duration of the post-test stage. This paper presents the localization of only one-time damages, but the works over the use of correlation classifier for double damage parameter are in progress. However, this requires for any potential pair of defective elements, the use of at least four patterns of damage, for example, +25% and +25%, +25% and -25%, -25% and -25%, and -25% and +25%. In this case, the number of dictionary inputs grows rapidly and with it - the time of pre-test and post-test calculations. The effectiveness of the method can be improved by adding a second measuring node.

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