A Fault Diagnosis Expert System Structure with Knowledge Retrieving Capability from Waveforms

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Abstract - **Analogue fault diagnosis can be addressed by expert systems using artificial intelligence methodologies. The structure of such an expert system and its main features are presented in this paper. As a special feature, knowledge which is obtained through the waveforms of specific parameters of the circuit under test is presented. Techniques for comparison between waveforms and conclusion extraction are described. Demonstrative examples of fault location using the expert system are given.**

Index Terms - analogue circuits, expert systems, analogue fault diagnosis

I. INTRODUCTION

In the last three decades analogue fault diagnosis has been addressed using various methodologies depending on the electronic structure of the system under test [1-6]. Artificial intelligence approaches have also been proposed [7-19], mainly to support test engineers to face the increasing complexity and size of modern systems, resulting in "fault diagnosis expert systems".

In this work the structure of a fault diagnosis expert system that uses selected methodologies of artificial intelligence is proposed. Particular importance is given in the way of knowledge retrieving via waveforms of specific parameters of the circuit under test and the importance of information from graphical data. Methods for the comparison of this information are described and the need of a method that exports logical more than numerical results becomes obvious. Application in particular electronic circuit follows and finally certain useful conclusions are reported.

II. GENERAL CHARACTERISTICS OF THE EXPERT SYSTEM STRUCTURE

The structure of the proposed expert system, which consists of three interconnected sections, is shown in figure 1, along with the main features of each section. The knowledge retrieving section enhances the expert system with the behaviour of good (non-faulty) tested systems. Its main features are: man-machine interaction, functional models, modules description, logic rules and inductive learning. The most important feature is the use of waveforms which describe certain characteristics, like: input-output transfer function, voltage or current waveforms, voltage-current characteristic, power supply current waveform or its spectrum. Graphical presentations of the above characteristics are commonly included in the technical manuals of electronic circuits and they can be easily transferred into a fault diagnosis expert system.

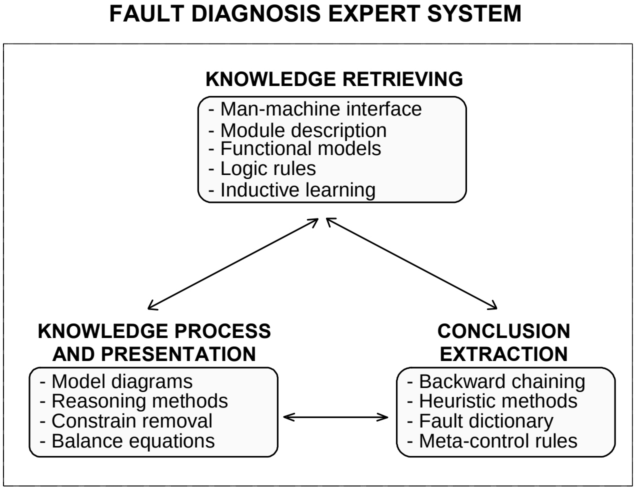

Figure 1. Fault Diagnosis Expert System structure.

The knowledge presentation and process section increases the knowledge of the expert system using model diagrams, the technique of removal of constrains, balance equations or reasoning methods. The conclusion extraction section increases the success of fault diagnosis by applying backward chaining, meta-control rules, fault dictionary or heuristic methods.

III. COMPARISON OF GRAPHICAL REPRESENTATIONS

Knowledge extraction through graphical data can be accomplished by comparing the waveforms of the good known system to the waveforms of the tested one. There are techniques [20-25] which use mathematical relations to compare the waveforms and extract arithmetic results. A comparison technique having the ability to extract efficient logical results would be of great interest for the proposed approach.

The input-output transfer function is very often used as a way of description of circuit behaviour and it is given in the technical handbooks, therefore it is easy to be imported in the expert system. It is known that the transfer function expresses the circuit output for inputs that cover a wide range of the spectrum of frequency response. A circuit output point can be examined by choosing a small number of entries in suitable frequencies and with the comparison of measured output data with the corresponding one that result from the transfer function waveform from known good circuit. These comparisons are simple numerical calculations and they can take into consideration the tolerances of circuit components and parameters. Consequently, the import of waveforms from the technical handbook is not only to make a simple copy to the computer but it must include the process of transformation the waveform to numerical data.

The use of simple mathematical methods (e.g. minimal square, Euclidian distance) to compare waveforms does not always conclude to positive results mainly because of the particular shape of waveforms. Thus, the criterion described above must be useful for logical comparison between the known-good and the faulty waveforms.

Let x(t) and y(t) be two periodic signals with period T. The autocorrelation function for the x(t) can be written as:

$$r_{xx}(\alpha) = \frac{1}{T}\int_0^T x(t)x(t+\alpha)dt \tag{1}$$

The cross-correlation function between x(t) and y(t) is:

$$r_{xy}(\alpha) = \frac{1}{T}\int_0^T x(t)y(t+\alpha)dt \tag{2}$$

In the following, the above correlation functions will be applied for $\alpha=0$ with the notations:

$$R_{xx} = r_{xx}(0) \quad , \quad R_{xy} = r_{xy}(0) \tag{3}$$

Let the known non-faulty waveform be denoted by x(t) and the measured one by $x^m(t)$. If their difference is written as: $\Delta x(t) = x(t) - x^m(t)$, then it can be easily shown that:

$$r_{\Delta x \Delta x}(0) = R_{\Delta x \Delta x} = R_{xx} + R_{x^m x^m} - 2R_{xx^m} \geq 0 \tag{4}$$

$$R_{xx} + R_{x^m x^m} \geq 2R_{xx^m}$$

Two criteria based on the autocorrelation and cross-correlation functions are usually applied to express the similarity between two signals. For x(t) and $x^m(t)$, these criteria are defined by:

$$K_1 = \frac{R_{xx^m}}{R_{xx} + R_{x^m x^m} - R_{xx^m}} \tag{5}$$

$$K_2 = \frac{R_{xx^m}}{(R_{xx}\, R_{x^m x^m})^{1/2}} \tag{6}$$

When x(t) is exactly the same with $x^m(t)$, then:

$$R_{xx} = R_{xx^m} = R_{x^m x^m} \tag{7}$$

In many practical occasions the signature identification or the fault diagnosis relies upon the discrimination of nearly similar waveforms. Therefore, in case where R_{xx^m} is negative the two waveforms are considered completely different, thus only the cases for which it is:

$$R_{xx^m} > 0 \tag{8}$$

are of practical interest in our analysis.

Using the relations (4),(7) and (8) and a known property of the cross-correlation function which can be written as:

$$R_{xx^m} \leq (R_{xx}\, R_{x^m x^m})^{1/2} \tag{9}$$

it can be shown that the K_1 and K_2 are normalized measures of similarity, since it is: $0 < K_1 \leq 1$ and $0 < K_2 \leq 1$. Furthermore, for a given pair of waveforms x(t) and $x^m(t)$, it can be proved, under the condition (8), that:

$$K_1 \leq K_2 \tag{10}$$

Relation (10) implies that for a given pair of waveforms x(t) and $x^m(t)$ and under condition (8), the use of K_1 generally results in a better discrimination than K_2, since K_1 gives a smaller similarity. Nevertheless, the application of the K_1 criterion in a variety of almost similar waveforms shows that its discrimination capability was poor. Therefore, a weighting factor w is introduced in order to improve discrimination. This factor w basically incorporates the difference (absolute value) between the autocorrelation of the compared waveforms and it is defined as:

$$w = 1 - \frac{|R_{xx} - R_{x^m x^m}|}{(R_{xx}\, R_{x^m x^m})^{1/2}} \tag{11}$$

If the two signals are exactly similar, then eqn. (7) holds and this factor equals to unity. The new criterion is now defined as:

$$K_3 = wK_1 = \\ = \left(1 - \frac{|R_{xx} - R_{x^m x^m}|}{(R_{xx} R_{x^m x^m})^{1/2}}\right)\frac{R_{xx^m}}{R_{xx} + R_{x^m x^m} - R_{xx^m}} \tag{12}$$

and it is also normalized with values $0 < K_3 \leq 1$. Furthermore, it can be easily proved that it is:

$$K_3 \leq K_1 \tag{13}$$

which implies that K_3 criterion gives better discrimination than K_1 and K_2.

Using this new criterion, which uses the autocorrelation and cross-correlation functions, the similarity of the waveforms is calculated as percentage value, giving the possibility of testing the waveforms from analogue circuits more efficiently. It must be noticed that storing various waveforms and creating a fault dictionary of known-good and faulty waveforms can be used in order to export conclusions on the situation of examined circuit. Using this method of comparison we can change from simple mathematical comparison in a logical comparison that can be used more easily with an expert system.

Meanwhile, in digital and mixed-mode electronic circuits the supply current testing can be applied [21]. For the comparison of supply current waveforms the technique that has been presented in [22], have been proposed, that uses the auto-regressive model which comes from the maximum, minimum and medium values of the current and gives satisfactory results taking into consideration the form of the examined currents. Apart from the comparison, this technique provides also the possibility of classification of current, helping in the export of logical conclusions. Also, the use of the spectrum of this supply current and the definition of a descrimination factor gives positive results in analogue circuits [23-25]. The combination of these two methods can be used to the expert system in order to cover digital and mixed-mode circuits.

IV. APPLICATIONS

The module diagram of a band stop filter, also used as a benchmark circuit in [4,5,7,24,25], is shown in figure 2 along with the circuit diagram of the filter in figure 3. The known-good frequency responses of each module are shown in figures 4-7 and they can be easily imported in the expert system.

For the examination of the circuit in module level the input and output measurements are enough. The frequency response in its complete form requires a big number of measurements, but it can be easily extracted and stored. The frequency response waveform is compared with the known good frequency response of the circuit (figure 7) using the K_3 criterion described in the previews section. If the two waveforms are similar within an adjustable tolerance limit (e.g. 97%) then it can be considered that the circuit function is non-faulty. Otherwise a fault is realised and examination in sub-circuit level is required for the final fault diagnosis of the circuit.

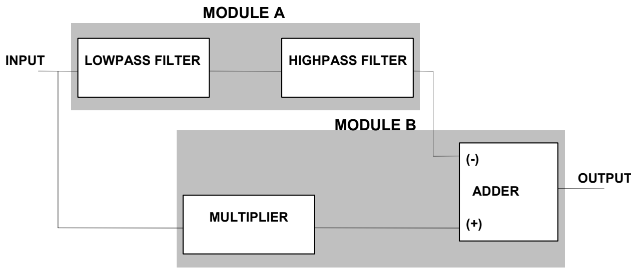

Figure 2. Module diagram of the examined band stop filter.

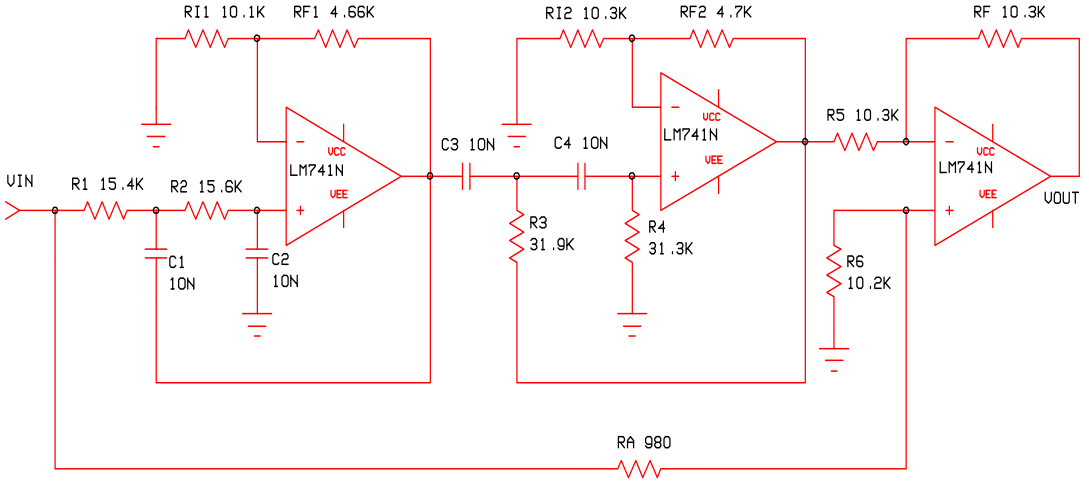

Figure 3. Circuit diagram of the examined band stop filter.

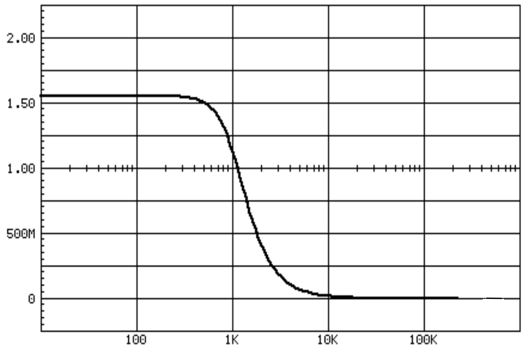

Figure 4. Frequency response of the low-pass filter.

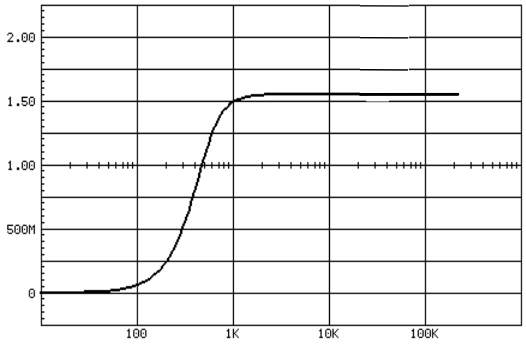

Figure 5. Frequency response of the high-pass filter.

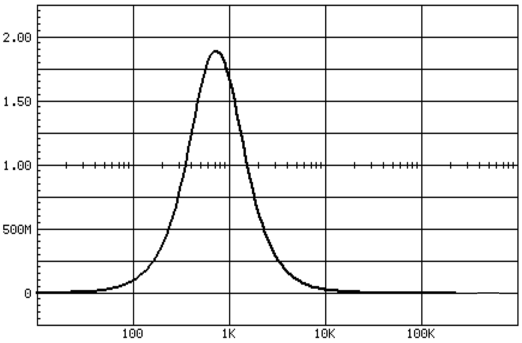

Figure 6. Frequency response of the band pass filter.

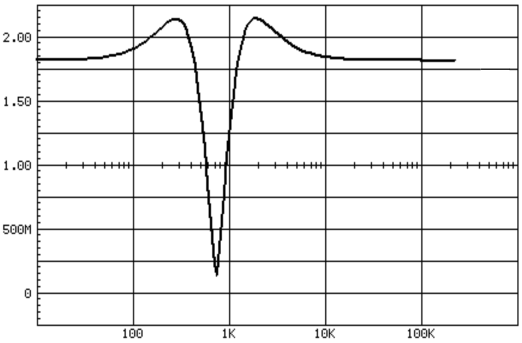

Figure 7. Frequency response of the output of the examined band stop filter circuit.

The meta-control rule is used for the selection of the next control. The selection of the low-pass filter output gives information only for the low-pass filter sub-circuit, while the selection of non-inverting input of the adder gives information only for the multiplier sub-circuit. Meanwhile, the selection of output of module A gives information for the entire module A. The conclusion is easily reached by following the signal flow through the sub-circuits. This heuristic method is an essential characteristic of the expert system and shows that the output of module A offers additional information and is proposed as the next test.

The output of module A is examined using the same criterion (figure 6). If it is found non-faulty, then the fault is located in module B, otherwise it is located in module A. In the second case the use of a waveform identification procedure can achieve diagnosis in sub-circuit level.

For waveform identification, as a first step a simple classification procedure is suggested to be applied in advance of the application of the K_3 criterion in order to reduce the total time required for the comparisons. The given waveform with autocorrelation $R_{x^m x^m}$ is classified in a group of signatures with autocorrelation R_{xx} in the range: $R_{x^m x^m} \pm (\varepsilon\%) \cdot R_{x^m x^m}$. A heuristic value of $\varepsilon\% = 20\%$ gave satisfactory results in many examples. This heuristic is not crucial and does not restrict the extrapolation of the procedure to general circuits, since the final comparison is expected to be between almost similar waveforms with small percentage differences (e.g. 0 to 10%) in $R_{x^m x^m}$ and it will be accomplished by the application of the K_3 criterion. Special attention was given in cases where $R_{x^m x^m}$ was less than unity, which implies that the signal has very small mean-square value; in such cases all waveforms with $R_{xx} < 1$ where grouped together and the given waveform was compared to all of them. This classification and identification procedure using at first the values of R_{xx} and then the K_3 criterion can be used for automatic recognition of unknown waveforms.

For example, in case of fault where the high-pass filter behaves as voltage follower, the above described identification procedure conclude to reasonable extraction if the frequency response of the voltage follower has been already stored and examined. Thus, the use of a well informed database for waveform identification becomes crucial.

The frequency response in its complete form requires a big number of measurements. Thus, another method to examine the particular circuit using three measurements in characteristic frequencies seems to be enough. So, three different input frequencies are selected, one below the cut-off frequency (e.g. 200 Hz), another one above the cut-off frequency (e.g. 5 KHz) and another one very near to the cut-off frequency (e.g. 700 Hz). The input-output gain for each one of them is measured. If the gain is equal with the corresponding one from the known good frequency response of circuit (figure 7) then it can be considered that the circuit function is non-faulty. Otherwise a fault is realized and examination in sub-circuit level is required for the final fault diagnosis of the circuit. The output of module A is examined using the same way (figure 6). If it is found non-faulty, then the fault is located in module B, otherwise it is located in module A.

Let's suppose the output of module A good, thus the fault is located in module B and the examination is continued in a sub-circuit level. An additional measurement point is required in the positive input of the adder. The known mathematical expression between the input and the output of an adder can be used for the examination. If this mathematical expression occurs then the fault is located in the multiplier sub-circuit, otherwise it is located in the adder sub-circuit.

Using the above process, fault location in sub-circuit level was achieved. For fault location in component-level more measurements and points of control are required. It is obvious that the measurement points should increase while the fault diagnosis procedure and results are transported in lower levels.

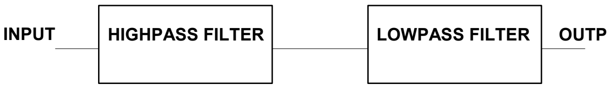

Figure 8. Module diagram of the band-pass filter.

After the knowledge retrieving from the low-pass and high-pass filter, the expert system has the knowledge of functional models of these sub-circuits. The module diagram that appears in figure 8 is a band-pass filter that is constituted by these two sub-circuits. The fault diagnosis of this band-pass filter circuit becomes henceforth easier for the expert system, with the use of functional models of these sub-circuits.

V. CONCLUSIONS

The proposed expert system structure includes known artificial intelligence methodologies in order to increase the reliability and the ability of testing various electronic systems. The knowledge obtained and stored in module level from the tested systems and the known inductive learning procedures, makes the expert system flexible and "smart" and, therefore, able to test circuits and systems more effectively.

Using the frequency response waveforms of the modules of a band stop filter and the expert system features referenced above, fault diagnosis was obtained. Other systems which consist of modules already described in the expert system, such as a band-pass filter, can also be addressed successfully. Specific testing procedures can be easily "learned" by the expert system using inductive learning.

As it is found from the application, the crowd of measurements and points of control it depends from the desirable level of diagnosis. The comparison of the measured with the known good waveforms with methods that give numerical results provides more information that found accurate for the diagnosis of the specific circuit. Comparison methods, based on the functional sub-circuit models and on fault dictionary approaches, which are capable to give reasonable results more than arithmetical results, provide more information and improve the efficiency of the expert system.

REFERENCES

[1] F. Garzia, "Fault isolation computer methods", NASA Contractor rep. NASA CR-1758, Marshall Space Flight Center, Huntsville, Alabama, Feb. 1971.

[2] D. Bedrosian, Special Issue on Automatic Analog Fault Diagnosis, IEEE Trans. Circuits & Systems, vol. 26, July 1979.

[3] R. W. Liu et al., "Analog Fault Diagnosis: A new circuit theory", IEEE Int. Symp. on Circuits & Systems, USA, May 1983.

[4] J. W. Bandler, and A. E. Salama, "Fault diagnosis of analog circuits", Proc. IEEE, vol. 73, Aug. 1985, 1279-1325.

[5] R. W. Liu, ed., Selected papers on Analog Fault Diagnosis, IEEE Press Inc., 1987.

[6] R. W. Liu, ed., Testing and Diagnosis of Analog Circuits and Systems, Van Nostrand Reinhold, 1991.

[7] R. R. Cantone, F. J. Pipitone, W. B. Lander, and M. P. Marrone, "Model-Based Propabilistic Reasoning for Electronic Troubleshooting", Proc. Eighth Int. Joint Conf. on Artificial Intelligence, Karlsruhe, West Germany, 1983, 207-211.

[8] M. Merry, "APEX-3: An Expert System Shell for Fault Diagnosis", GEC J. of Research, vol. 1, No. 1, 1983, 39-47.

[9] F. J. Pipitone, "An Expert System for Electronics Troubleshooting Based on Fuction and Connectivity", IEEE First Conf. on Artificial Intelligence Applications, Denver, Dec. 1984, 133-138.

[10] A. A. Hatzopoulos, and J. M. Kontoleon, "Computer Simulations of Testing Procedures for Fault Diagnosis in Analog Circuits", AMSE Modelling, Simulation and Control, vol. 8, no. 2, Autumn 1986, 37-48.

[11] F. Pipitone, "The FIS Electronics Troubleshooting System", IEEE Computer Magazine, Jul. 1986, 68-76.

[12] A. Wakeling, A. McKeon, "On Automatic fault finding in analogue circuits", Electronic Engineering, Nov. 1989, 95-101.

[13] A. A. Hatzopoulos, "Fault Diagnosis of Electronic Systems using computer", 3rd Hellenic Information Conference, Athens, May 1991, 576-589 (in Greek).

[14] G. Kontos, and K. D. Spyropoulos, "Artificial Intelligence in Fault Diagnosis of Electronic Systems", 1st Hellenic Information Conference, Athens, 1986, 40-53 (in Greek).

[15] S. Tzafestas, "Automated Fault Diagnosis and Supervision of industrial processes using Expert Systems", 2nd Hellenic Information Conference, Thessaloniki, 1988, 576-589 (in Greek).

[16] F. Pipitone, K. DeJong, and W. Spears, "An Artificial Intelligence Approach to Analog Systems Diagnosis", Chapt. 7 in Testing and Diagnosis of Analog Circuits and Systems, R. W. Liu, ed., Van Nostrand Reinhold, 1991.

[17] Huang JT, Liao YS, "A wire-EDM maintenance and fault-diagnosis expert system integrated with an artificial neural network", Int. J. of Production Research, Vol. 38, No 5, pp. 1071-1082, Mar 2000.

[18] Lee HJ, Ahn BS, Park YM, "A fault diagnosis expert system for distribution substations", IEEE Tr. On Power Delivery, Vol. 15, No 1, pp. 92-97, Jan 2000.

[19] Wu HQ, Liu Y, Ding YL, Qiu YQ, "Fault diagnosis expert system for modern commercial aircraft", Aircraft Engineering and Aerospace Technology, Vol. 76, No 4, pp. 398-403, 2004.

[20] D. K. Papakostas, and A. A. Hatzopoulos, "Correlation-Based Comparison of Analog Signatures for Identification and Fault Diagnosis", IEEE Trans. on Instrumentation and Meaurements, vol. 42, no. 4, August 1993.

[21] Hawkins, C. F. et al.: "Quiescent Power Supply Current Measurement for CMOS IC Defect Detection", IEEE Trans. on Industrial Electronics, vol. 36, no. 2, 1989, 211-218.

[22] M. Hashizume, and T. Tamesada, "Fault Detection of TTL Combinational Circuits Based on Supply Current", Systems and Computers in Japan, vol. 22, no. 10, 1991, 18-29.

[23] D. K. Papakostas, and A. A. Hatzopoulos, "Analogue Fault Identification Based on Power Supply Current Spectrum", IEE Electronics Letters, vol. 29, no. 1, Jan. 1993, 118-119.

[24] Papakostas D.K., Hatzopoulos A.A., "Detection of Time Delay Related Faults using Fourier Phase Components of Power Supply Current", IEE Electronics Letters, Vol. 40, No. 1, pp. 7-8, January 2004.

[25] Papakostas D.K., Hatzopoulos A.A., "Analogue Fault Detectability Comparison Between Power Supply Current and Output Voltage Magnitude and Phase Spectrum Components", IEE Electronics Letters, Vol. 40, No. 8, pp. 457-458, April 2004.