AN APPROACH TO ANALOGUE CIRCUITS TEST BASED ON APPLICATION OF NEURAL NETWORK AND WAVELET DECOMPOSITION

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This paper deals with approach to analogue circuits functional test. The neural network is used as signature classifier providing detection catastrophic and parametric faults. Wavelet decomposition as preprocessing of circuit's output responses allows generating the signatures. Using of transient responses gives possibility to keep and take into account the dynamical characteristics of analogue circuits during testing. The experimental results of proposed approach and comparison with other methods are shown.

Keywords: Analogue circuits testing, neural networks, wavelet decomposition

1. INTRODUCTION

Realization of analogue circuits test and diagnosis automatically deals with various difficulties, such as nonlinear and continuos character of the input signal transformation; complex functional dependence between input and output signals; high sensitivity of output parameters to variation of in-circuit and external parameters; tolerances on component parameters; presence of two possible types faults parametric and catastrophic, etc. Presence of parametric faults makes ineffective and often impossible to use methods of structural test for analog circuits. Parametrical test of analogue circuits is carried out usually using functional approach, which consists in verification of all circuit specifications. A circuit is accepted as fault-free if all specifications are satisfied, otherwise an analog circuit is considered as faulty.

All techniques of analogue circuits test can be split into two basic categories: estimation methods, based on measurement and evaluation of absolute values for output signal's characteristics, and pattern (signature) recognition methods, based on classification by matching the measurement data. The methods of the second category allow partitioning the measured data on specified decision subspaces. Such task can be realized using mechanism of artificial neural network (NN).

Several neural network based approaches to analogue circuit have been proposed [1]–[6]. In [1], classification of faults in linear analogue circuits is performed using backward error propagation network. The training signatures are generated on the base of circuit's impulse response. The large NN architecture even for small size circuits is the result of using output response without pre-processing. In [2], authors propose to use the coefficients of response's wavelet decomposition as signature for the neural network training. Wavelet decomposition allows reducing number of inputs to the NN. The limited number of coefficients and principal component analyses provide the reduction of the neural network's complexity.

The robust heteroscedastic probabilistic NN for fault detection and classification using four AC and DC output characteristics is proposed in [3]. Here the special feed-forward NN with complex architecture is used for increasing accuracy of correct classification.

The wavelet neural network (WNN) using wavelet base instead of sigmoid function is considered in [4]. Here wavelet transform and neural networks are combined for fault diagnosis. High complication of the WNN for complex analogue circuits is the weak side of this approach.

In [5] and [6], authors propose to use power supply current as investigated characteristics for catastrophic fault detection. The Kohonen network is trained in the [5] for signature classification. In [6], the feed-forward NN and wavelet decomposition are used in order to classify defect-free and defective circuits.

In this paper the technique of functional testing both linear and non-linear analog circuits is presented. In contrast to approaches considered above, this technique is based on transient test using measurement of voltages in the test nodes [7], [8]. The sine wave signal with variable frequency is proposed as input test stimuli. Transient waveforms are able to test the complete dynamic behavior of analog circuits, especially nonlinear, and provide capability to detect larger number of faults then AC and DC tests. Test analyzer, proposed in the paper, is realized as artificial neural network. Here one-time training of NN, which is performed on the stage of a circuit under test (CUT) design, allows to get structure of the NN-based test analyzer and use it then on the stages of the circuit implementations and exploiting. One of the significant features of NN-based technique is possibility of on-line testing.

2. Background of Transient Functional Test

The main goal of functional test is to verify correctness of CUT specifications. Functional test consists in three basic steps: 1) generation of input test signals; 2) verification of CUT output responses on given test inputs; 3) decision making about circuit correctness. A set of input test signals constitutes the test vector. Circuit's nodes, to which input signals are applied and from which output characteristics are measured, are called test nodes.

During functional test the following tasks should be decided: 1) selection of estimated parameters; 2) selection of input exciting signals' type; 3) realization of responses analysis; 4) estimation of fault coverage.

2.1 Selection of estimated parameters

In this paper wavelet decomposition is used for selection of essential characteristics of CUT during transient test.

Wavelet decomposition of one-dimension signal is defined as:

$$W(a,b) = \int_{-\infty}^{\infty} f(t)\psi^*_{a,b}(t)dt\,, \tag{1}$$

where $$\psi_{a,b}(t) = \frac{1}{\sqrt{|a|}}\psi\left(\frac{t-b}{a}\right). \tag{2}$$

Wavelet decomposition is a function of two variables. For a given $a, \psi_{a,b}(t)$ is a shift of mother wavelet $\psi_{a,0}(t)$ by an amount b along time axis. The variable b represents time shift. Factor $1/\sqrt{|a|}$ provides independence of norm for $\psi_{a,b}(t)$ from the dilation a.

Wavelet decomposition of output response of investigated analogue circuit allows to get information about all spectral constituents with different level of detail with multiple resolution. Coefficients of wavelet decomposition of responses measured concerning output test nodes are used as estimated parameters during transient functional test. Such pre-processing allows to reduce the dimension of investigated output responses without significant loss of quality.

2.2. Selection of input test signal

The harmonic sinusoidal signals with variable both frequency and amplitude are used as the input test stimuli. Such choice is explained by simplicity of sine wave generation and by different influences of the signal frequencies on the CUT performance. The selection of optimal frequencies for input test signal, improving testability of analogue circuits, allows reducing a set of applied test influences and number of used test nodes. The frequencies of input test signal are defined by criteria of maximum the output characteristic sensitivity to variations of internal and external circuit parameters.

Quantity estimation of influence some component or circuit characteristic on change of output function is defined as the following (3)

$$S_x^F = \frac{\partial F}{\partial x}, \tag{3}$$

where S_x^F is sensitivity function, F is differentiable circuit function, x is internal circuit parameter.

Frequency selection is performed in small-signal mode. In frequency domain sensitivity is complex conjugated function, therefore sensitivity for gain and phase functions are expressed by equations (4) and (5) accordingly.

$$\frac{\partial |F|}{\partial x} = |F| \operatorname{Re}\left(\frac{\partial F}{\partial x}\frac{1}{F}\right), \tag{4}$$

$$\frac{\partial (\arg F)}{\partial x} = \operatorname{Im}\left(\frac{\partial F}{\partial x}\frac{1}{F}\right)\frac{180}{\pi}. \tag{5}$$

Sensitivity can be considered as observability factor depending on the frequency of input signal, which shows influence of in-circuit parameter deviation on output characteristics. The larger the sensitivity function $S_x^F(\omega)$, the larger influence of parameter x on output characteristic F, where ω is frequency of input signal. Minimal number of frequencies providing maximum of output characteristics' sensitivity function to variations of in-circuit components defines the test vector frequencies.

These frequencies will provoke maximum reflection of possible faults in output characteristics.

2.3. Response analysis realization

For detecting the investigated circuit's status (faulty/fault-free) it is necessary to perform response analysis, which consists in comparison of CUT output characteristics with responses of etalon (fault-free) circuit at each test signal from test vector. Analogue circuits is faulty (by definition), if any of specifications are violated.

The multilayer neural network is used for realizing response analysis. The syndromes obtained during wavelet decomposition of output responses both faulty and fault-free circuit are used for the NN training. In result of significant characteristics extraction the matrix $\mathbf{X} \subseteq \Re(s, r)$ is formed. Each row of this matrix reflects circuit's behavior using one of s measurements. The columns represent r coefficients of wavelet decomposition of output response s. So, each row of matrix **X** is used as input pattern for training NN and therefore the input layer contains r neurones. The training of neural network for functional testing is realized by collection of s input vectors. Each training vector is represented by the following pair

$$s_i = (x_i, y_i),$$

where x_i is i-th row of matrix **X** (i-th input pattern), y_i is associated vector, which defined by equation (6)

$$y_i = \begin{cases} 0, \text{ if circuit is fault-free at } i\text{-th measurement;} \\ 1, \text{ if circuit is fauly at } i\text{-th measurement.} \end{cases} \quad (6)$$

The collection of test vectors is formed using Monte-Carlo simulation of fault-free and faulty circuit, and wavelet decomposition of output reactions in the test nodes. In proposed approach the error backpropagation algorithm is used for the neural network training.

3. Realization of Functional Test Approach

The NN trained using wavelet decomposition coefficients is used for analogue circuits testing. The test process consists in two stages – training stage and testing stage. Selection of neural network structure and its training are performed for each analogue circuit during training stage. The process of neural network training can be described by the following algorithm:

1. Selection of test frequencies and test nodes using sensitivity analysis.
2. $i = 0$.
3. Simulation of fault-free circuit behavior by Monte Carlo method. $i = i + 1$.
4. Realization of wavelet decomposition of transient output responses in test nodes.
5. Construction of i-th input vector s_i, where coefficients of wavelet decomposition obtained on previous step are used as x_i, and y_i is equal 0 that corresponds to fault-free circuit status.

6. If $i \le N_{ff}$ then go to step 3, otherwise go to step 7. N_{ff} is limiting number of Monte Carlo iterations for fault-free circuit.

7. Simulation of faulty circuit behavior by Monte Carlo method using casual inclusion of faults (parametric, catastrophic, single and multiple). $i = i + 1$.

8. Realization of wavelet decomposition of faulty circuit's transient output responses in test nodes.

9. Construction of i-th input vector s_i, where coefficients of wavelet decomposition obtained on previous step are used as x_i, and y_i is equal 1 that corresponds to faulty circuit status.

10. If $i \le N_{ff} + N_f$ then go to step 7, otherwise go to step 11. N_f is limiting number of Monte Carlo iterations for faulty circuit.

11. Repeat steps from 3 to 10 for each test frequencies.

12. Training of neural network by $N_{ff} + N_f$ input vectors.

13. Using neural network for the analogue circuit test.

The NN obtained in result is used further for testing the circuit. The circuit under test investigation is performed on testing stage. Reaction of NN on input pattern is the result of signature analysis: CUT is good – "0" or CUT is failed – "1".

4. Experimental Results and Comparison

The Sallen-Key bandpass filter was used for study as in [1], [2] and [4]. The circuit is a bandpass filter with a nominal center frequency of 25 kHz (Fig. 1). All initial conditions were used as in [1], [2] and [4] in order to compare the obtained results of proposed approach with those. All resistors and capacitors have tolerances of 5 % and 10 % respectively. The eight fault classes were selected. These faults deal with parameters' deviation of components $R2$, $R3$, $C1$ and $C2$ on 50 % higher and lower from their respective nominal values.

Sensitivity analysis of the filter provides selection of test frequencies; i.e. such frequencies that guarantee maximum value of sensitivity for considered components. After simulation the following frequencies were selected: 19 kHz and 23.868 kHz.

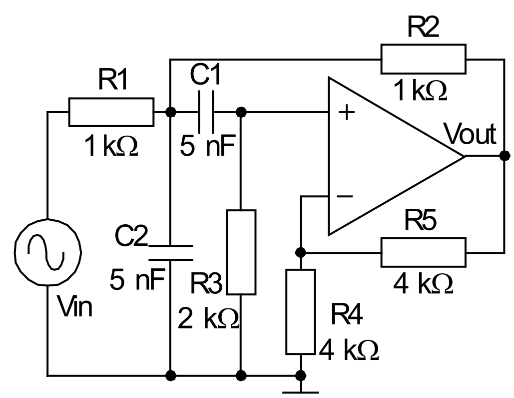

Fig. 1. 25 kHz Sallen-Key bandpass filter

Using Monte Carlo iterations 6 400 output responses were generated, 3 200 for fault-free condition and 3 200 for faulty condition of the filter. The single fault model was used at each iteration taking into account tolerances of other components. Only 1 260 responses both faulty and fault-free conditions of the circuit were used during the training phase, residuary responses were applied during testing phase.

The three-layer backpropagation neural network with 25 inputs (essential characteristics of output voltage, obtained during wavelet decompositions), 15 first-layer and 10 second-layer neurons was used for response analyzis realization. Mother wavelet 'db8', which provides higher distance between faulty and fault-free responses, was selected for wavelet decomposition. Using approach proposed in this paper the NN provides 98.4 % fault detection, in contrast to [1] and [2], where NNs provide only 95 % and 97 % respectively. The complexity of used neural network is essentially lower than in [4], and time costs on training are significantly shorter. The training of neural network with precision of 0.01 takes only 414 epochs.

Application of proposed approach to ITC'97 analog benchmark circuits allows to get high fault detection and shows efficiency of this approach.

5. Conclusions

In this paper the transient functional approach to testing linear and non-linear analogue circuits has been presented.

Trained neural network allows detecting both catastrophic and parametric faults, which provide essential violation of the circuit functioning. Some faults are masked and not detected. This effect deals with non-essential deviations of output responses in test nodes, when output characteristic is within the tolerance range. In this case, CUT is defined as fault-free.

The efficiency of the approach provides high fault coverage even for simple topology of the NN. The time required on response analysis is enough low, less 1 sec. Misclassification error consists of less 2 %.

This approach provides possibility to test the mixed-signal circuits thanks to digitised output response of neural network-based test analyser. The future development of this approach implies the realisation of the test analyser in hardware and investigation of in-circuit test cost and efficiency.

6. References

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