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Soft fault diagnosis of linear circuits with the special attention paid to the circuits containing current conveyors

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ABSTRACT

This paper deals with soft fault diagnosis of linear analog circuits and concentrates on the circuits including second generation current conveyors. Properties of these circuits are taken into account and an appropriate realistic conveyor model is put forward. The fault diagnosis includes fault detection, locating faulty elements from among all circuit elements, and estimating their values. The diagnostic method developed in this paper exploits a measurement test in an AC state and uses the nonlinear programming as a mathematical tool. Values of the faulty parameters may belong to wide ranges around their nominal values. For illustration a real-life current conveyor circuit is laboratorily and numerically tested. Proposed method efficiently diagnoses different faults giving correct results in short time. Although the method is dedicated to single fault diagnosis, it can be generalized to double and triple faults either. However, in the case of multiple faults it is less effective.

1. Introduction

Fault diagnosis of analog circuits has been an active research topic for the past decades, e.g. [2,3,6,10,11,21,25,26]. It helps in reducing the overall cost of devices due to imperfect manufacturing process [21]. Soft fault diagnosis includes fault detecting, locating faulty elements and estimating their values. Most reported works are focused on the diagnosis of a single fault, e.g. [8,28,30] because the single fault case is the most frequent. Some methods in this area are based on a measurement test leading to a set of nonlinear equations with variables being the circuit parameters. The more variables, the more complex and time consuming the process of solving the test equations is. To simplify the diagnostic process a fault verification approach can be applied, e.g. [16,22–24]. It is based on the hypothesis that only some of the parameters are potentially faulty and the others are fault-free. In this manner the number of the variables is reduced, but a drawback of this approach is the need for selecting the possibly faulty elements. Unlike the verification approach the goal of the diagnosis method proposed in this paper is to find faulty elements (and evaluate their values) from among all the circuit elements. Although huge number of research works have been reported in the past decades there is no all-purpose procedure for soft fault diagnosis of a broad class of circuits. The diagnosis procedure developed in this paper can be applied to linear circuits including passive and active devices with the special attention paid to the current conveyor circuits. It takes into account specific properties of this class of circuits and inherent limitations.

Most of the practical circuits belonging to the above-discussed class include up to four current conveyors and several typical circuit elements. In such case the number of the diagnosed parameters is usually less than twenty. When the overall circuit is manufactured as IC it suffers from limited accessibility through terminals for excitation and measurement. To arrange diagnostic test a frequency response function (transmittance) is formulated in symbolic form and the corresponding output voltage is measured in the frequency domain for several values of frequencies. They enable finding the transmittance values at these frequencies. Comparing them with the symbolic form of the transmittance a system of diagnostic equations is written. To determine the faulty parameters which meet both diagnostic equations and required constraints the nonlinear programming (NLP) [29] with the objective function being an arbitrary constant is employed.

The second-generation current conveyor CCII is a four-terminal semiconductor device. The terminals X , Y, Z, and the external ground are indicated in the standard conveyor symbol in Fig. 1.

Here, I_X, I_Y, and I_Z denote the currents entering the device, while V_X, V_Y, and V_Z denote the voltages between terminals X , Y, Z and the external ground. CCII is described by the system of three equations

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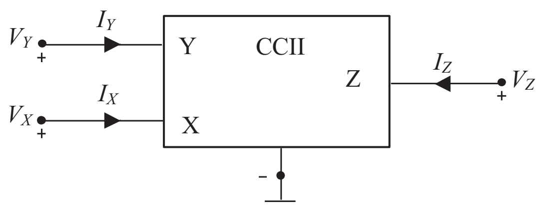

Fig. 1. Standard conveyor symbol.

$$I_Y = 0 \tag{1}$$

$$V_X = \beta V_Y \tag{2}$$

$$I_Z = \alpha I_X \tag{3}$$

where $\beta = 1$, $\alpha = \pm 1$. Depending on the sign of α the conveyor is labelled CCII+ (if $\alpha = 1$) or CCII- (if $\alpha = -1$). Eqs. (1)–(3) describe an ideal CCII.

Second generation current conveyors are useful in design of analog circuits. They simplify realization of complex functions and offer many advantages over operational amplifiers [7,18] enabling realization of almost all the circuits exploiting operational amplifiers.

The CCII is a versatile and flexible building block for different applications, both linear and nonlinear, discussed in detail in the reference [18]. Linear applications include: design of amplifiers, integrators, and differentiators, e.g. [5,7]; impedance simulations, e.g. [15]; analog filter design, e.g. [20]; realization of sinusoidal oscillators, e.g. [19]. Nonlinear applications include: realization of precision rectifiers, e.g. [1]; design of multipliers, dividers, squares, rooters, e.g. [12]; realization of analog switches, e.g. [14]; implementation of chaotic circuits, e.g. [17].

Both a BJT and a CMOS technology can be used to fabricate current conveyor integrated circuits. Realization of CCII in a BJT technology is shown e.g. in [18,27] whereas realization in a CMOS technology is presented e.g. in [9,13,18].

Realistic model of CCII for low frequency applications is shown in Fig. 2. It includes a voltage–controlled voltage source (VCVS), a current–controlled current source (CCCS) and two resistors R_X and R_Z. Typically $R_X \leqslant 50\ \Omega$ and $R_Z > 1\ \mathrm{M\Omega}$. If $R_X = 0$ and $R_Z \to \infty$ we obtain the ideal model described by the Eqs. (1)–(3).

Soft fault diagnosis discussed in this paper considers the faulty parameters including quantities α and β and resistances R_X and R_Z which describe current conveyors as well as resistances, inductances, and capacitances of the circuit components. Deviation of the CCII parameters from their nominal values can occur due to some local variations in the integrated circuit that realizes the conveyor. If local variations of some transistor parameters, in the circuit creating CCII, occur then the conveyor parameters can vary. In soft fault case usually $|\alpha|$ and β remain rather close to 1, but the values of R_X and R_Z may change substantially as illustrated in the following example.

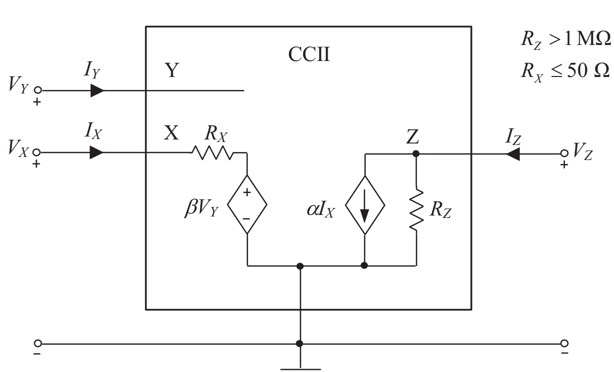

Fig. 2. Realistic model of CCII.

Example 1. Let us consider the low–pass filter shown in Fig. 3, including CCII+, driven by an AC voltage source having the amplitude 0.5 V. The CCII+ is designed in a CMOS technology (model BSIM3v3) and consists of 15 MOS transistors as shown in the reference [9, Fig. 2]. This CMOS CCII+ can be represented by the model depicted in Fig. 2 with the parameters: $\alpha = 1$, $\beta = 1$, $R_X = 0.06\ \Omega$, $R_Z = 10\ \mathrm{M\Omega}$. The amplitude and the phase characteristics of the filter obtained using this CCII+ model and its CMOS representation, shown in Figs. 4 and 5, are identical. This confirms correctness of the model.

When the channel length of the transistor M13 deviates from 2.5 μm to 2.4 μm, the parameters of the CCII+ model become: $\alpha = 0.9982$, $\beta = 0.9998$, $R_X = 0.0603\ \Omega$, $R_Z = 88.66\ \mathrm{k\Omega}$. In this case the amplitude and the phase characteristics of the filter obtained using the CCII+ model and its CMOS representation are still identical, but they differ considerably from the ones depicted in Figs. 4 and 5. The differences are visualized in Figs. 6 and 7. Therefore the local parameter deviation in the circuit which realizes the conveyor causes variation of all the parameters of its model and indicates that the conveyor is faulty. In consequence of this fault the filter functionality is violated. Generally, if at least one parameter of the model exceeds some limits defined in Sections 2 and 3 the conveyor is considered faulty.

Most of the papers devoted to the analysis and design of circuits containing current conveyors apply the ideal model of CCII. However, in fault diagnosis of this class of circuits the ideal model is inadequate and the realistic one shown in Fig. 2 is necessary.

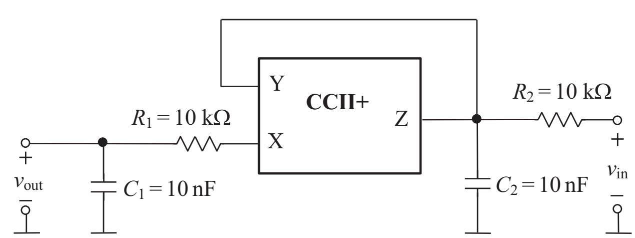

Fig. 3. Low pass–filter including a CCII+.

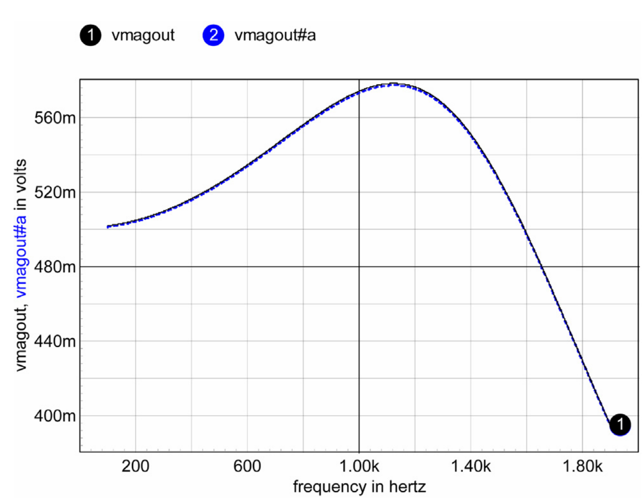

Fig. 4. The amplitude characteristics (1 and 2 coincide).

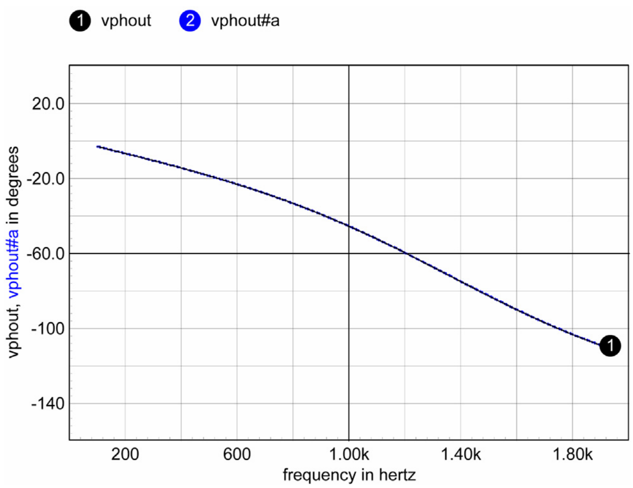

Fig. 5. The phase characteristics (1 and 2 coincide).

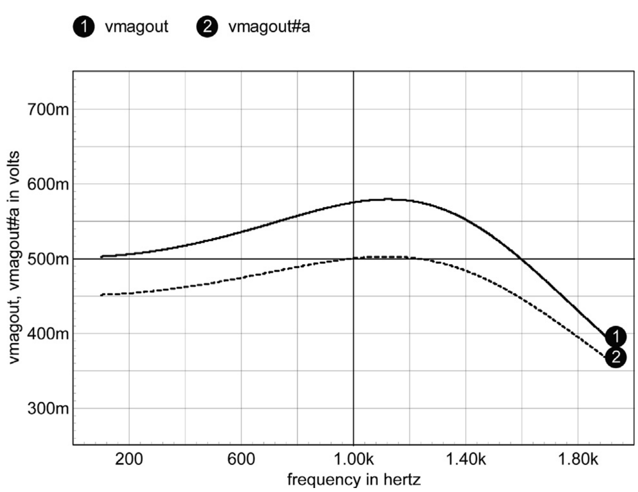

Fig. 6. The amplitude characteristics of the filter with unfaulty (1) and faulty (2) conveyor.

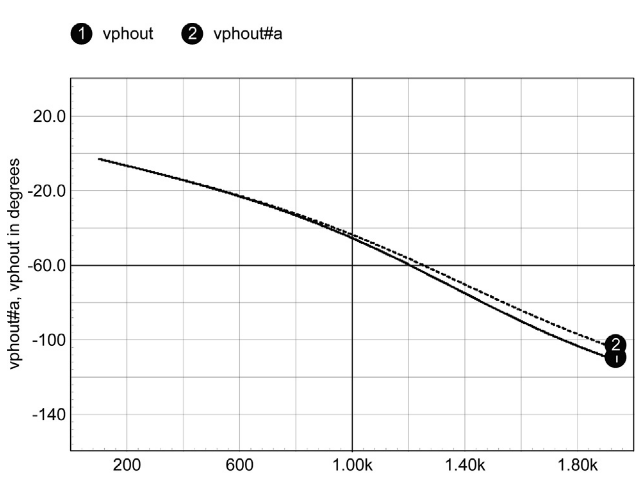

Fig. 7. The phase characteristics of the filter with unfaulty (1) and faulty (2) conveyor.

2. Method for soft fault diagnosis

Consider a linear circuit, containing current conveyors as well as resistors, inductors and capacitors, with one node accessible for excitation and one node accessible for measurement and create the frequency response function $f(\mathbf{x},\ \omega)$. It depends on the angular frequency ω and the parameters $x_1, \ldots, x_n$ forming vector $\mathbf{x} = [x_1\ \cdots\ x_n]^{\mathrm{T}}$, where T denotes transposition. The function can be presented as

$$f(\mathbf{x},\ \omega) = \hat{f}(\mathbf{x},\ \omega) + \mathrm{j}\hat{\hat{f}}(\mathbf{x},\ \omega) \tag{4}$$

where $\hat{f}(\mathbf{x},\ \omega)$ is its real part and $\hat{\hat{f}}(\mathbf{x},\ \omega)$ is its imaginary part. Let the function $f(\mathbf{x},\ \omega)$ be given in symbolic form. While running the diagnostic test the output voltage is measured at frequencies $\omega_1, \ldots, \omega_l$ and the corresponding values of $f(\mathbf{x},\ \omega)$ are calculated. They are labelled $a_1 + \mathrm{j}\,b_1, \cdots, a_l + \mathrm{j}\,b_l$. Hence, the diagnostic equations can be written as

$$f(\mathbf{x},\ \omega_k) = a_k + \mathrm{j}\,b_k, k = 1, \ldots, l. \tag{5}$$

The above l equalities between complex numbers are equivalent to $m = 2l$ equalities between real numbers

$$\begin{aligned} p_1(\mathbf{x}) &= \hat{f}(\mathbf{x},\ \omega_1) - a_1 = 0 \\ &\ \vdots \\ p_l(\mathbf{x}) &= \hat{f}(\mathbf{x},\ \omega_l) - a_l = 0 \\ p_{l+1}(\mathbf{x}) &= \hat{\hat{f}}(\mathbf{x},\ \omega_1) - b_1 = 0 \\ &\ \vdots \\ p_m(\mathbf{x}) &= \hat{\hat{f}}(\mathbf{x},\ \omega_l) - b_l = 0\ . \end{aligned} \tag{6}$$

To describe the diagnostic method we consider a circuit containing M conveyors and N circuit elements (resistors, inductors, and capacitors). Any conveyor is specified by four parameters α, β, R_X and R_Z. The circuit parameters are resistances, inductances, and capacitances. Denoting the parameters by x_k we form the vector $\mathbf{x} = [x_1 \cdots x_4 \cdots x_{4M-3}\ x_{4M-2}\ x_{4M-1}\ x_{4M}\ x_{4M+1}\ \cdots\ x_n]^{\mathrm{T}}$, where $n = 4M + N$. Thus, the circuit is represented by the n-dimension vector of the parameters. Any parameter x_k, except R_Z, is considered as fault free if it meets the inequality $\left|x_k - x_k^0\right| \leqslant \varepsilon_k$, where x_k^0 is the nominal value and $\varepsilon_k = \frac{1}{100}\hat{\varepsilon}_k x_k^0$, where $\hat{\varepsilon}_k$ is tolerance of the element in percents. Parameter x_k being R_Z is considered as fault free if $R_Z^{\min} \leqslant R_Z \leqslant R_Z^{\max}$. Any parameter whose value exceeds the range defined above is said to be faulty. If at least one conveyor parameter is faulty the conveyor is considered as faulty.

We seek for faulty parameters being resistances, inductances, capacitances, α, β, and R_X in the ranges $\left|x_k - x_k^0\right| \leqslant \delta_k$, where $\delta_k > \varepsilon_k$. In the case of resistance R_Z the range is $R_Z^- \leqslant R_Z \leqslant R_Z^+$ (see Section 3).

First step of the fault diagnosis is checking whether the circuit under the test can be considered as fault free as described in the following. If the circuit is declared faulty a procedure for locating the faulty elements and evaluating their values is applied. We consider every single one element in succession and check whether it is faulty under the assumption that all other elements are fault free. To this end the nonlinear programming (NLP) is used. The conditions required by NLP are created for each of the tested elements as described in the sequel. In each of the $M + N$ cases the NLP either states that the element is faulty or fails. As a result one or several or none element can be identified as faulty. Existing more than one faults means that each of them meets the diagnostic test and they are equally valid. It can occur due to existing ambiguity groups in the circuit [4]. If the NLP fails in all the cases then several faulty elements occur simultaneously.

To explain the NLP used in the diagnostic procedure we consider a circuit including two conveyors specified by the parameters $x_1 = \alpha_1$, $x_2 = \beta_1$, $x_3 = R_{X_1}$, $x_4 = R_{Z_1}$, $x_5 = \alpha_2$, $x_6 = \beta_2$, $x_7 = R_{X_2}$, $x_8 = R_{Z_2}$, and three circuit elements specified by the parameters x_9, x_{10}, x_{11}. In this circuit $M = 2, N = 3$, and the number of elements is $M + N = 5$. The procedure of seeking a single faulty element requires applying five different nonlinear programming relating to each of the elements. When a conveyor, say conveyor 1, is considered the NLP is as follows.

NLP for diagnosing conveyor 1

Find an optimal point $\mathbf{x}^* = \left[x_1^* \cdots x_{11}^*\right]^{\mathrm{T}}$ to max(arbitrary constant)

subject to

$$|x_1 - x_1^0| \le \delta_1, |x_2 - x_2^0| \le \delta_2, |x_3 - x_3^0| \le \delta_3, R_Z^- \le x_4 \le R_Z^+,$$

$$|x_k - x_k^0| \le \varepsilon_k, k = 5, ..., 11, k \ne 8, R_Z^{\min} \le x_8 \le R_Z^{\max},$$

$$|p_i(\mathbf{x})| \le \mu_i, i = 1, ..., m$$

where μ_i are small positive numbers depending on required accuracy.

The other conveyor is tested in the same way.

When one of the parameters x_9, x_{10}, x_{11} is tested the NLP is as follows.

NLP for diagnosing parameter x_k $(k \in \{9, 10, 11\})$

Find an optimal point $\mathbf{x}^* = \left[x_1^* \cdots x_{11}^*\right]^{\mathrm{T}}$ to max(arbitrary constant)

subject to

$$\left|x_k - x_k^0\right| \leqslant \delta_k$$

$$|x_i - x_i^0| \le \varepsilon_i, i = 1, ..., 11, i \ne k, i \ne 4, i \ne 8$$

$$R_Z^{\min} \le x_i \le R_Z^{\max}, i = 4, 8$$

$$|p_i(\mathbf{x})| \le \mu_i, i = 1, ..., m.$$

Procedure for checking if the circuit is fault free is as follows. Apply NLP as

find an optimal point $\mathbf{x}^* = \left[x_1^* \cdots x_{11}^*\right]^{\mathrm{T}}$ to max(arbitrary constant)

subject to

$$|x_k - x_k^0| \le \varepsilon_k, k = 1, ..., 11, k \ne 4, k \ne 8,$$

$$R_Z^{\min} \le x_k \le R_Z^{\max}, k = 4, 8$$

$$|p_i(\mathbf{x})| \le \mu_i, i = 1, ..., m.$$

If all parameters of $\mathbf{x}^*$ are inside their tolerance limits the circuit is fault free.

The algorithm for fault diagnosis is shown in Fig. 8.

3. Illustration of the method

Method proposed in Section 2 has been implemented in MATLAB and tested using several conveyor circuits. The calculations were performed on PC with processor Intel Core i7–6700.

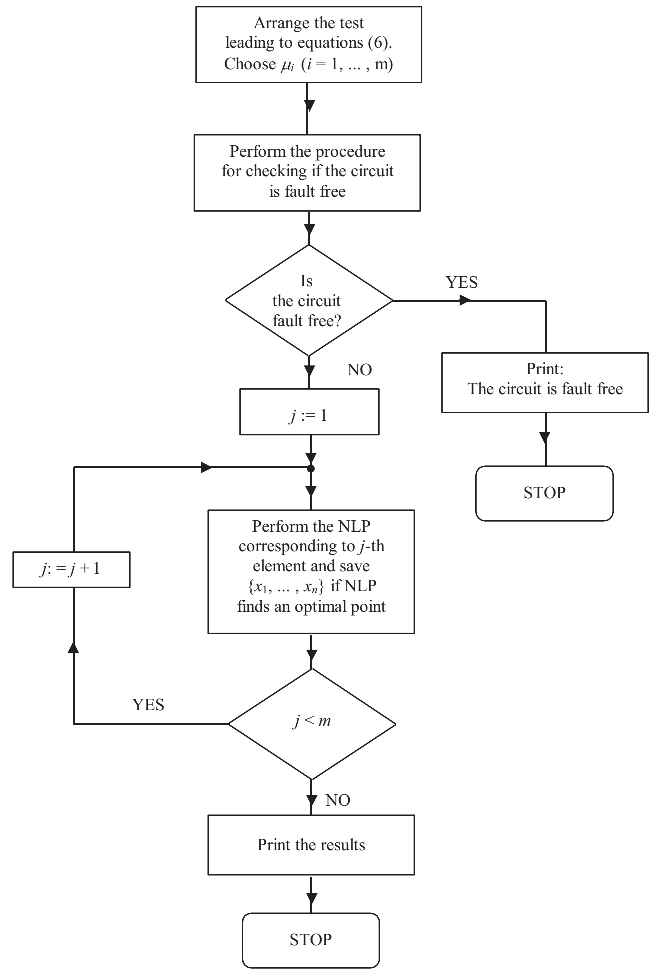

Fig. 8. Flowchart of the diagnostic algorithm.

Example 2. To illustrate effectiveness of the method we consider the circuit shown in Fig. 9, based on the filter proposed in the reference [18, p.162]. Experimental measurement has been performed by implementing the scheme on prototype PCB using commercially available AD844. It provides external access to the Z-terminal (as the compensation pin) that makes it possible to use it as a CCII + [18, p.7, 18, p. 53]. The circuit includes $M = 3$ conveyors and $N = 5$ circuit elements, hence the number of the tested elements is $M + N = 8$. The number of the parameters is $n = 4M + N = 17$ and their nominal values are: $x_1 = \alpha_1 = 1$, $x_2 = \beta_1 = 1$, $x_3 = R_{X_1} = 50\ \Omega$, $x_4 = R_{Z_1} = 3\ \mathrm{M\Omega}$ (see the AD844 Data Sheet), $x_5 = \alpha_2 = 1$, $x_6 = \beta_2 = 1$, $x_7 = R_{X_2} = 50\ \Omega$, $x_8 = R_{Z_2} = 3\ \mathrm{M\Omega}$, $x_9 = \alpha_3 = 1$, $x_{10} = \beta_3 = 1$, $x_{11} = R_{X_3} = 50\ \Omega$, $x_{12} = R_{Z_3} = 3\ \mathrm{M\Omega}$, $x_{13} = R_1 = 6.800\ \mathrm{k\Omega}$, $x_{14} = R_3 = 10.000\ \mathrm{k\Omega}$, $x_{15} = C_2 = 33.00\ \mathrm{nF}$, $x_{16} = C_4 = 82.00\ \mathrm{nF}$, $x_{17} = R_5 = 20.000\ \mathrm{k\Omega}$. Tolerances of the resistors R_1, R_3, R_5 and the capacitors C_2 and C_4 are equal to 2%, tolerance of resistor R_X is 5%, tolerances of the parameters α and β are 0.1% and the range which defines unfaulty resistor R_Z is $\left[R_Z^{\min} = 2.7\ \mathrm{M\Omega},\ R_Z^{\max} = 20\ \mathrm{M\Omega}\right]$. The ranges where the parameters are seeking in the course of the diagnosis are: $\left|x_k - x_k^0\right| \leqslant 0.5x_k^0$ for R_1, R_3, R_5, C_2, C_4, R_X, $\left|x_k - x_k^0\right| \leqslant 0.2x_k^0$ for α and β, and $R_Z^- = 10^{-3}\ \mathrm{M\Omega} \leqslant x_k \leqslant R_Z^+ = 20\ \mathrm{M\Omega}$ for $x_k = R_Z$.

The diagnostic test is arranged in the circuit driven by an AC voltage source having the amplitude 2 V for l = 20 frequencies belonging to the scope [200, 1150] Hz with the step 50 Hz. In the course of the test the parameters were properly scaled.

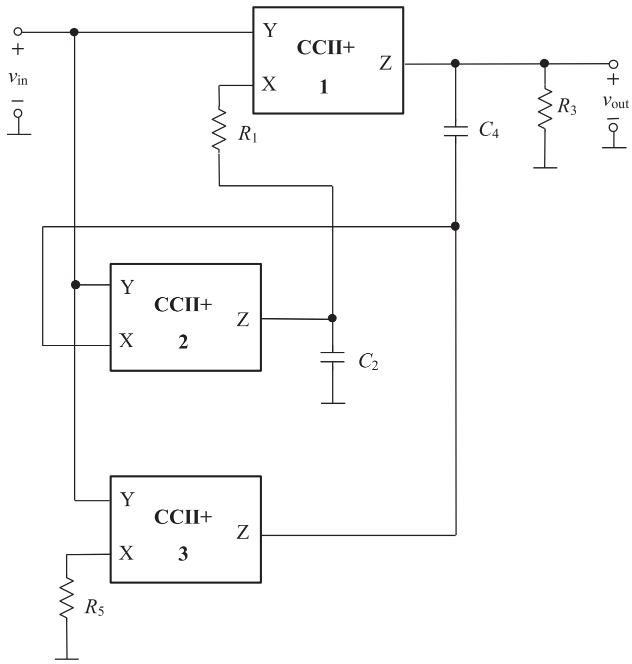

Fig. 9. An exemplary filter.

Table 1
Results of laboratory fault diagnoses of the elements R_1, C_4, C_2.

Tested element	Nominal, actual and determined values	The other parameters provided by the method
R_1	$R_1^0 = 6.800$ kΩ $R_1^{\mathrm{act}} = 4.679$ kΩ $R_1 = 4.598$ kΩ	$R_3 = 9.845$ kΩ, $C_2 = 33.66$ nF, $C_4 = 83.25$ nF, $R_5 = 20.40$ kΩ, $\alpha_1 = 0.9990$, $\beta_1 = 0.9991$, $R_{X_1} = 47.82$ Ω, $R_{Z_1} = 2.93$ MΩ, $\alpha_2 = 0.9990$, $\beta_2 = 0.9990$, $R_{X_2} = 49.85$ Ω, $R_{Z_2} = 3.22$ MΩ, $\alpha_3 = 0.9990$, $\beta_3 = 0.9990$, $R_{X_3} = 50.78$ Ω, $R_{Z_3} = 2.72$ MΩ
C_4	$C_4^0 = 82.00$ nF $C_4^{\mathrm{act}} = 99.50$ nF $C_4 = 98.44$ nF	$R_1 = 6.866$ kΩ, $R_3 = 9.842$ kΩ, $C_2 = 33.66$ nF, $R_5 = 20.40$ kΩ, $\alpha_1 = 1.0010$, $\beta_1 = 1.0010$, $R_{X_1} = 50.49$ Ω, $R_{Z_1} = 2.91$ MΩ, $\alpha_2 = 1.0010$, $\beta_2 = 1.0010$, $R_{X_2} = 51.37$ Ω, $R_{Z_2} = 3.10$ MΩ, $\alpha_3 = 0.9990$, $\beta_3 = 0.9990$, $R_{X_3} = 50.34$ Ω, $R_{Z_3} = 2.85$ MΩ
C_2	$C_2^0 = 33.00$ nF $C_2^{\mathrm{act}} = 22.16$ nF $C_2 = 21.94$ nF	$R_1 = 6.936$ kΩ, $R_3 = 9.800$ kΩ, $C_4 = 83.47$ nF, $R_5 = 20.00$ kΩ,$\alpha_1 = 1.0005$, $\beta_1 = 0.9990$, $R_{X_1} = 52.07$ Ω, $R_{Z_1} = 2.83$ MΩ, $\alpha_2 = 1.0010$, $\beta_2 = 1.0010$, $R_{X_2} = 52.47$ Ω, $R_{Z_2} = 3.08$ MΩ, $\alpha_3 = 0.9990$, $\beta_3 = 0.9990$, $R_{X_3} = 50.00$ Ω, $R_{Z_3} = 3.01$ MΩ

Table 2
Results of numerically diagnosed faulty elements

Faulty element	Nominal value	Actual value	Value given by the method
R_1	6.800 kΩ	4.700 kΩ	4.643 kΩ
R_3	10.000 kΩ	14.500 kΩ	14.728 kΩ
C_2	33.000 nF	18.000 nF	18.437 nF
C_4	82.000 nF	102.000 nF	101.420 nF

Several faulty and unfaulty circuits were laboratory tested, with the real values of the unfaulty parameters which slightly deviate from their nominal values. The NLPs were applied with $\mu_i = 0.05$, $i = 1, \ldots, 8$.

For an unfaulty circuit the method gives the set of parameters $\{x_1 = 1.0001,\ x_2 = 0.9990,\ x_3 = 50\ \Omega,\ x_4 = 3\ \mathrm{M\Omega},\ x_5 = 1.0010,\ x_6 = 1.0010,\ x_7 = 50\ \Omega,\ x_8 = 3\ \mathrm{M\Omega},\ x_9 = 0.9990,\ x_{10} = 0.9990,\ x_{11} = 50\ \Omega,\ x_{12} = 3\ \mathrm{M\Omega},\ x_{13} = 6.740\ \mathrm{k\Omega},\ x_{14} = 9.916\ \mathrm{k\Omega},\ x_{15} = 32.98\ \mathrm{nF}, x_{16} = 82.00\ \mathrm{nF}, x_{17} = 20.02\ \mathrm{k\Omega}\}$. All the parameters belong to the tolerance ranges which reveals that the circuit is fault free.

The results provided by the method in the circuit with chosen faulty elements R_1, C_4, C_2, are summarized in Table 1. In all the cases the method correctly locates the faulty elements and evaluate their values, whereas the other parameters given by the method are within the tolerance ranges.

Moreover, various faults in the circuit were diagnosed numerically assuming the accuracy 0.001 V of the tested voltage and $\mu_i = 0.001$. The diagnoses included 3 unfaulty circuits, 30 circuits with different values of faulty parameters R_1, R_3, C_2, C_4, R_5, and 12 circuits with different faulty conveyors. In all the cases including R_1, R_3, C_2, C_4 the method correctly locate the faulty element and estimates its value. Some of them are summarized in Table 2.

For different faults of resistors R_5 the method either gives a unique correct solution or the correct solution and a virtual one. Some chosen results are presented in Table 3.

From among 12 tested circuits containing faulty conveyors in 10 cases the method gives correct solution, i.e. determines the set of the conveyor parameters including at least one faulty parameter. In 2 cases the method determines the correct solution and a virtual one. Three chosen results are summarized in Table 4.

4. Some discussion and concluding remarks

Method proposed in this paper is dedicated to fault diagnosis of linear circuits and concentrates on the circuits containing current conveyors. Advantages of the method are as follows.

- The method includes all aspects of fault diagnosis: fault detection, locating faulty elements, and estimating their values.
- The diagnostic test exploited by the method is easy to arrange and uses standard measurement instrumentation.
- The method requires access to two nodes only.
- The method is easy to implement.
- All elements are considered as potentially faulty and the values of the faulty elements can belong to wide ranges around their nominal values.
- For single fault diagnosis the method is very effective and does not require great computing power.

The conveyor model for fault diagnosis put forward in this paper is a realistic representation of current conveyors. It cannot be replaced by the ideal model, commonly used in the analysis and design of conveyor circuits. Moreover, the model includes typical circuit elements which simplifies the analysis of the circuit at the preliminary step of the diagnosis.

Requirement of some initial activity, namely computing a frequency response function in symbolic form, is a drawback of the method. It can be obtained either by hand or using a program for symbolic analysis.

Although the method described in Section 2 is focused on single fault diagnosis it can be directly generalized to double fault diagnosis. In such case the algorithm is more time consuming because it works with all double combinations of the elements from among all the elements. However, the main drawback of the generalized version of the method is that it often provides, except the correct solution, some virtual solutions. Certain exemplary results of double fault laboratory diagnoses are shown in Table 5. These

Table 3
Results of numerically diagnosed faulty resistor R_5

Nominal value	Actual value	Results provided by the method
20.000 kΩ	12.000 kΩ	$R_5 = 12.266$ kΩ
20.000 kΩ	15.000 kΩ	$R_5 = 15.140$ kΩ - correct CCII 3 ($\alpha_3 = 1.1416$, $\beta_3 = 1.1416$, $R_{X_3} = 50.00\ \Omega$, $R_{Z_3} = 3.00$ MΩ) - virtual
20.000 kΩ	29.000 kΩ	$R_5 = 28.448$ kΩ - correct CCII 3 ($\alpha_3 = 0.8390$, $\beta_3 = 0.8390$, $R_{X_3} = 50.00\ \Omega$, $R_{Z_3} = 3.00$ MΩ) - virtual

Table 4
Results of numerically diagnosed conveyors

Faulty conveyor	Results provided by the method	Final result
CCII 1	$\alpha_1 = 1.1419$, $\beta_1 = 1.0019$, $R_{X_1} = 54.29\ \Omega$, $R_{Z_1} = 2.95$ MΩ	Conveyor 1 is faulty
CCII 2	$\alpha_2 = 1.0032$, $\beta_2 = 0.8508$, $R_{X_2} = 50.00\ \Omega$, $R_{Z_2} = 3.00$ MΩ	Conveyor 2 is faulty
CCII 3	$\alpha_3 = 0.8077$, $\beta_3 = 0.8077$, $R_{X_3} = 50.00\ \Omega$, $R_{Z_3} = 3.00$ MΩ	Conveyor 3 is faulty

Table 5
Results of laboratory double fault diagnoses

Faulty elements	Solutions determined by the method
$R_1 = 4.679$ kΩ $C_4 = 67.90$ nF	Correct solution Faulty elements: $R_1 = 4.687$ kΩ and $C_4 = 64.89$ nF Virtual solution 1 Faulty elements: $C_4 = 51.07$ nF and conveyor CCII 1 Virtual solution 2 Faulty elements: $R_1 = 3.983$ kΩ and conveyor CCII 2 Virtual solution 3 Faulty elements: $R_1 = 3.748$ kΩ and conveyor CCII 1
$R_1 = 4.679$ kΩ $R_3 = 12.02$ kΩ	Correct solution Faulty elements: $R_1 = 4.625$ kΩ and $R_3 = 11.806$ kΩ

inconvenient features occur in the case of triple fault diagnosis even in stronger form. Therefore, in the case of multiple faults the method is less effective. This is why the method is offered for single fault diagnosis.

The method can be applied to more general class of linear circuits including passive and active devices after proper modification of NLP.

Declaration of Competing Interest

The authors declare no conflict of interest.

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