Annals of DAAAM for 2012 & Proceedings of the 23rd International DAAAM Symposium, Volume 23, No.1, ISSN 2304-1382
ISBN 978-3-901509-91-9, CDROM version, Ed. B. Katalinic, Published by DAAAM International, Vienna, Austria, EU, 2012
Make Harmony between Technology and Nature, and Your Mind will Fly Free as a Bird
Annals & Proceedings of DAAAM International 2012

NON-PARAMETRIC METHOD FOR FAULT DIAGNOSIS IN ELECTRICAL CIRCUITS

FILARETOV, V[ladimir] F[edorovich]; ZHIRABOK, A[lexey] N[il] & TKACHEV, D[aniil]

Abstract: *The paper is devoted to the problem of fault diagnosis in electrical circuits described by linear or nonlinear polynomial models. So-called non-parametric method for fault detection is considered. This method assumes that parameters of the circuit under consideration may be unknown. It does not use methods of identification and allows detecting whether or not parameters of some elements deviate considerably from their nominal values.*
Keywords: *electrical circuit, linear models, polynomial models, fault detection, non-parametric method*

1. INTRODUCTION

Electrical circuits are a convenient model for describing different technical objects such as transformers, synchronous and asynchronous electrical machines, drives, and so on. For this reason electrical circuits are the subject of investigation for developing the fault diagnosis procedures. In the past decades several approaches to the diagnosis of circuits have been developed (see, for example, [9]). The majority of papers considering the problem of fault diagnosis in electrical circuits use different methods of identification ([1, 3, 4, 8, 13]). These methods allow providing an exhaustive analysis (in particular, determining values of parameters of the circuit) but demand comprehensive information about the circuit and are of high computational complexity. At the same time, in practice, one needs only to know that parameters of some elements deviate considerably from the nominal values.

Besides there are other approaches to fault diagnosis in electrical circuits:

– the simulation of a circuit for different faults to generate training data for an artificial neural network is presented in [2, 14];

– the method of establishing a fault dictionary using Wavelet transform is developed in [12];

– in [6, 7] the probabilistic graphical models are used, here faulty components are identified by looking for high probabilities for values of characteristic magnitude that deviate considerably from the nominal values;

– the probabilistic model-based approach presented in [11] is formally founded and based on Bayesian network and arithmetic circuits;

– the method based on diagnostic observers developed in [5, 18, 19, 20] considers linear and nonlinear circuits as dynamic systems; it is necessary to stress that the method suggested in [20] can be used for diagnosis in electrical circuits containing non-smoth nonlinearities such as hysteresis and saturation.

In this paper, the method of fault detection in electrical circuits described by linear and nonlinear polynomial equations is suggested. This method does not use methods of identification and other mentioned above methods and allows detecting whether or not parameters of some elements of the circuit deviate considerably from their nominal values.

There exists a promising method of diagnosis in linear and nonlinear systems known as “model-free” or “data-driven” method (see, for example, the paper [15, 16]). The feature of this method is that parameters of the system under consideration may be unknown. In this paper, another way developing the above method is suggested. In some cases it allows decreasing complexity of calculations in comparison with the method considered in [15, 16].

This paper is organized as follows. In Section 2 the basic models of electrical circuits are considered. Section 3 gives a solution to linear circuits and a brief discussion about diagnosis in nonlinear circuits. Section 4 concludes the paper.

2. BASIC MODELS

It is assumed that the circuit under consideration contains resistors, capacitors, inductances, sources and may operate in non-stationary regime. The suggested method is based on the following general description of the circuit:

$$\begin{aligned} \dot{x}(t) &= Fx(t) + Gu(t), \\ y(t) &= Hx(t) + Bu(t) \end{aligned} \quad (1)$$

where $x(t)$ is the state vector whose components are voltages across the capacitors and currents through the resistors and inductances, $u(t)$ is the vector whose components are values of the sources, $y(t)$ represents measured components of the state vector; F and G are constant matrices describing a structure of the circuit and values of the resistors, capacitors, and inductances, H and B are constant matrices describing measurements.

Vector equation (1) can be obtained on the basis of the equations

$$C\dot{U}(t) = I(t),$$
$$L\dot{I}(t) = U(t)$$

and Kirchhoff's laws.

Consider as an example the linear electrical circuit shown in Figure. Kirchhoff's laws describing the circuit are as follows:

$$I_1 = I_2 + I_5,$$
$$I_1 = I_3 + I_4,$$
$$R_1 I_5 + U_1 + U_3 = E,$$
$$R_2 I_2 + U_1 + U_2 + U_3 = E,$$
$$-R_3 I_4 + U_3 = E.$$

Using the equations

$$C_1\dot{U}_1(t) = I_1(t),$$
$$C_2\dot{U}_2(t) = I_2(t),$$
$$C_3\dot{U}_3(t) = I_3(t)$$

and assuming that

$$x = \begin{pmatrix} U_1 \\ U_2 \\ U_3 \end{pmatrix}, \quad y = \begin{pmatrix} U_1 \\ U_2 \end{pmatrix}, \quad u = E,$$

one obtains the following matrices in the model (1):

$$F = \begin{pmatrix} k_1 + k_2 & k_1 & k_1 + k_2 \\ k_3 & k_3 & k_3 \\ k_4 + k_5 & k_4 & k_4 + k_5 + k_6 \end{pmatrix},$$

$$G = \begin{pmatrix} -(k_1 + k_2) \\ -k_3 \\ -(k_4 + k_5 + k_6) \end{pmatrix},$$

$$H = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}, \quad B = 0$$

where

$$k_1 = -1/C_1R_2, \quad k_2 = -1/C_1R_1, \quad k_3 = -1/C_2R_2,$$
$$k_4 = -1/C_3R_2, \quad k_5 = -1/C_3R_1, \quad k_6 = -1/C_2R_3.$$

Note that if $y = \begin{pmatrix} U_1 \\ I_2 \end{pmatrix}$, then the matrices H and B take another form:

$$H = \begin{pmatrix} 1 & 0 & 0 \\ -1/R_2 & -1/R_2 & -1/R_2 \end{pmatrix}, \quad B = 1/R_2.$$

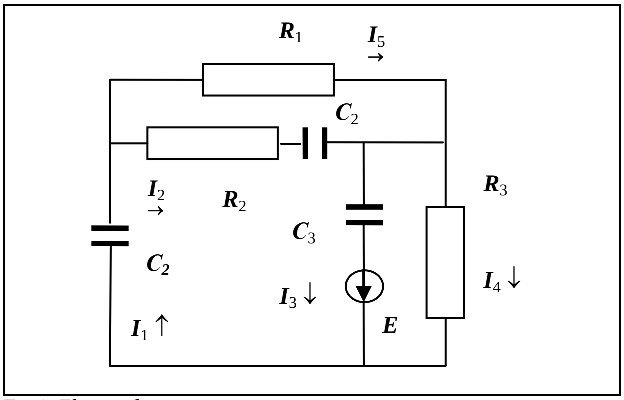

Fig.1. Electrical circuit

Assume that a class of faults in the circuit is a considerable deviation of resistance (for resistors) or capacity (for capacitors) from their nominal values. The problem is to design the method for fault detection assuming that parameters of the circuit are unknown.

3. PROBLEM SOLUTION

3.1 Basic relations

To develop the suggested method, consider the sampled-data model of the initial electrical circuit:

$$\begin{aligned} x(t+1) &= F'x(t) + G'u(t), \\ y(t) &= Hx(t) + Bu(t) \end{aligned} \qquad (2)$$

which can be obtained on the basis of the model (1). Assume that system (2) is observable therefore it can be presented in the identical canonical form [15, 20]. Consider some subsystem of this identical canonical form with the scalar output $y_*(t)$ and k-dimensional state vector $x_*(t)$. The components of this vector satisfy the equations

$$\begin{gathered} x_{*i}(t+1) = x_{*i+1}(t) + J_{*i}y(t) + G_{*i}u(t), \\ i = 1,2,\ldots,k-1, \\ x_{*k}(t+1) = J_{*k}y(t) + G_{*k}u(t), \\ y_*(t) = x_{*1}(t). \end{gathered} \qquad (3)$$

Equations (3) can be transformed into the single one by analogy with [18] as follows:

$$y_*(t+1) = x_{*1}(t+1) = J_{*1}y(t) + G_{*1}u(t) + x_{*2}(t),$$
$$y_*(t+2) = J_{*1}y(t+1) + G_{*1}u(t+1) +$$
$$J_{*2}y(t) + G_{*2}u(t) + x_{*3}(t),$$
$$\cdots$$
$$y_*(t+k) = \begin{pmatrix} J_{*1} & G_{*1} & \ldots & J_{*k} & G_{*k} \end{pmatrix} \begin{pmatrix} y(t+k-1) \\ u(t+k-1) \\ \vdots \\ y(t) \\ u(t) \end{pmatrix}.$$

The expression for the output $y_*(t+k)$ can be written for different instants of time as follows:

$$Y_*(N) = \left(y_*(t+k+N) \quad y_*(t+k+N-1) \quad \dots \quad y_*(t+k)\right) =$$
$$= (J_{*1} \quad G_{*1} \quad \dots \quad J_{*k} \quad G_{*k}) \times$$
$$\begin{pmatrix} y(t+k+N-1) & y(t+k+N-2) & \dots & y(t+k-1) \\ u(t+k+N-1) & u(t+k+N-2) & \dots & u(t+k-1) \\ \vdots & \vdots & \ddots & \vdots \\ y(t+N) & y(t+N-1) & \dots & y(t) \\ u(t+N) & u(t+N-1) & \dots & u(t) \end{pmatrix} =$$
$$(J_{*1} \quad G_{*1} \quad \dots \quad J_{*k} \quad G_{*k})\ V_N. \tag{4}$$

Note that all parameters of the system are contained in the matrix $(J_{*1} \quad G_{*1} \quad \dots \quad J_{*k} \quad G_{*k})$, the vector $Y_*(N)$ and the matrix V_N contain the measurements only. This allows performing diagnosis on the basis of $Y_*(N)$ and V_N and assuming that parameters of the system may be unknown. Note that the parity relation method is based on (4) as well but it supposes that parameters of the system are known [17].

In the case when the unknown parameters are in the matrices G_{*i} only, the expression (4) can be rewritten as follows:

$$Y_{**}(N) = Y_*(N) - (J_{*1} \quad \cdots \quad J_{*k}) \times$$
$$\begin{pmatrix} y(t+k+N-1) & y(t+k+N-2) & \dots & y(t+k-1) \\ \vdots & \vdots & \ddots & \vdots \\ y(t+N) & y(t+N-1) & \dots & y(t) \end{pmatrix} =$$
$$(G_{*1} \quad \cdots \quad G_{*k}) \times$$
$$\begin{pmatrix} u(t+k+N-1) & u(t+k+N-2) & \dots & u(t+k-1) \\ \vdots & \vdots & \ddots & \vdots \\ u(t+N) & u(t+N-1) & \dots & u(t) \end{pmatrix} =$$
$$\left(G_{*1} \quad G_{*2} \quad \dots \quad G_{*k}\right) V_N^u.$$

In this case the matrix V_N^u is used in further analysis instead of V_N. The advantage of such a presentation is that the dimension of the matrix V_N^u is far less than the one of the matrix V_N that allows decreasing complexity of calculations.

3.2 Decision making: algebraic approach

Consider rows of the matrix V_N (or V_N^u) as a set of the basis vectors of some hyperplane denoted by $\mathbf{L}(V_N)$ (or $\mathbf{L}(V_N^u)$); to be specific, the matrix V_N will be considered in the following. If the vector $Y_*(N)$ belongs to this hyperplane, then one concludes that the system is healthy. In the presence of disturbances, this vector may not belong to the hyperplane $\mathbf{L}(V_N)$ even in the faulty-free case; the value of distance between the vector $Y_*(N)$ and the hyperplane $\mathbf{L}(V_N)$ can be used for decision making on the basis of some threshold. Note that the minimal value of N can be defined as $N \geq \dim \mathbf{L}(V_N)$.

To calculate the distance distance between the vector $Y_*(N)$ and the hyperplane $\mathbf{L}(V_N)$, the following decomposition of the matrix V_N is used:

$$V_N = A \cdot \Sigma \cdot B, \tag{5}$$

where A and B are nonsingular matrices, $\Sigma = \left(I \quad 0\right)$. Such a decomposition can be obtained on the basis of singular value decomposition of the matrix V_N suggested for the purpose of diagnosis in [10].

Suppose that $Y_*(N) \in \mathbf{L}(V_N)$, i.e. the vector $Y_*(N)$ is a linear combination of the matrix V_N rows. Therefore the equation $Y_*(N) = CV_N$, or $Y_*(N) = C \cdot A \cdot \Sigma \cdot B$ holds for some matrix C. Compute the vector $Y = Y_*(N)B^{-1}$ and rewrite the previous expression in the form $Y = C \cdot A \cdot \Sigma$. It follows from this expression that the vector Y is a linear combination of the matrix $\Sigma = \left(I \quad 0\right)$ rows. This matrix allows concluding that the last element of the vector $Y = Y_*(N)B^{-1}$ is equal to zero in the faulty-free case. Denoting this element by Y_L, one can consider the equality $Y_L = 0$ as a parity relation. Therefore, to generate a residual, the following expression can be used:

$$r(N) = Y_L. \tag{6}$$

It follows from the structure of the matrix $\Sigma = \left(I \quad 0\right)$ that for the arbitrary vector $Y_*(N)$ the row C' exists such that the difference $Y_*(N)B^{-1} - C' \cdot A \cdot \Sigma$ is a vector with all zero components but the last one. This means that the value $r(N) = Y_L$ can be considered as a distance between the vector $Y_*(N)$ and the hyperplane $\mathbf{L}(V_N)$.

The decision making rule is as follows: if $r(N) = 0$, the system is health, otherwise the fault has occurred. In the presence of disturbances, the residual $r(N)$ must be compared with the threshold has to be determined. Notice that according to (5), this rule is not based on the system parameters, they may be unknown.

In the nonlinear case when the circuit contains nonlinear elements such as varicaps, varistors and so on described by polynomial models, one can use the considered approach as well. In this case matrices in the row $(J_{*1} \quad G_{*1} \quad \dots \quad J_{*k} \quad G_{*k})$ are replaced by coefficients of these polynomials (see the paper [15] for detail).

The circuit shown in Figure was modeled with $u = \sin(5t)$ and $y_* = U_1$; modeling results based on the rule (6) show the reliable fault detection for all elements in this circuit.

3.3 Decision making: geometric approach

Consider another approach to calculate the distance between the vector $Y_*(N)$ and the hyperplane $\mathbf{L}(V_N)$ (or $\mathbf{L}(V_N^u)$). It is well known that in 3-dimensional case the distance ρ between the point with coordinates (x_0, y_0, z_0) and the plane described by the equation $Ax + By + Cz + D = 0$ can be calculated as follows:

$$\rho = \frac{|Ax_0 + By_0 + Cz_0 + D|}{\sqrt{A^2 + B^2 + C^2}} \quad (7)$$

In the case when one considers the hyperplane $\mathbf{L}(V_N)$ (or $\mathbf{L}(V_N^u)$) with the basis presented by rows of the matrix V_N (or V_N^u), the above formula is generalized as follows:

$$r(N) = \frac{\sum_{i=1}^{k} (-1)^{i+1} Y_{*i} M_{1i}}{\sqrt{\sum_{i=1}^{k} M_{1i}^2}} \quad (8)$$

where M_{1i} is a minor corresponding to the first row of the matrix V_N (or V_N^u). The residual $r(N)$ must be compared with some threshold has to be determined.

4. CONCLUSIONS

The paper considers the problem of fault detection in electrical circuits described by linear and polynomial models. So-called non-parametric method to solve this problem is suggested. The feature of this method is that parameters of the circuit under consideration may be unknown. The suggested solution is based on singular value decomposition and geometric representation and allows decreasing complexity of calculations in comparison with the method considered in [15, 16] in some cases. The modeling results show the reliable fault detection for all elements in the circuit under consideration.

The future plan of reaserches is: (1) a comparison between the algebraic and geometric approaches; (2) a development of procedure to design the threshold; (3) an establishment of conditions under which fault isolation is possible.

5. ACKNOWLEDGEMENTS

This work was supported by Russian Foundation of Basic Researches, grants No 10-08-00133-a and 11-08-91151-GFEN.

6. REFERENCES

[1] Alpatova, A., Butyrin, A. & Alpatov, M. (2001). Identification of transformers, *Power engineering*, (4): 93-98 (in Russian)

[2] Aminian, F., Aminian, M. & Collins, H. (2002). Analog fault diagnosis of actual circuits using neural networks, *IEEE Trans. Instrumentation and Measurement*, 51(3): 544-550. ISSN 0018-9456

[3] Butyrin, P. & Alpatov, M. (1998). Continuous diagnosis of transformers, *Electricity*, (7): 46-55 (in Russian)

[4] Benlder, J. & Salama, A. (1985). Fault diagnosis in analog circuits, *Proc. IEEE*, 73: 1279-1325. ISSN 0018-9219

[5] Blanke, M., Kinnaert, M., Lunze, J. & Staroswiecki M. (2003). *Diagnosis and fault tolerant control*. Springer-Verlag, ISBN 3-540-01056-4, New York

[6] Borgelt, C., Girimonte, D. & Acciani, G. (2004). Modeling and diagnosis of analog circuits with probabilistic graphical models, *CD ROM Proc. IEEE Int. Symp. on Circuits and Systems*, ISBN 0-7803-8251-X Vancouver,. Canada

[7] Borgelt, C. & Kruse, R. (2005). Probabilistic Graphical Models for the Diagnosis of Analog Electrical Circuits, *Proc. 8th European Conf. on Symbolic and Quantitative Approaches to Reasoning and Uncertainty*, ISBN 978-3-540-27326-4 Barcelona, Spain

[8] Kinsht, N., Gerasimova, G. & Kats, M. (1983). *Diagnosis of electrical circuits*. Moscow: Energoatomizdat (in Russian)

[9] Liu, R.-W. (1991). *Testing and diagnosis of analogs circuits and systems*. Van Nostrand Reinhold, ISBN 978-0442259327, New York

[10] Lou X.; Willsky A. & Verghese G. (1986). Optimally robust redundancy relations for failure detection in uncertain systems. *Automatica*, 22: 333-344, ISSN 0005-1098

[11] Mengshoel, O., Chavira, M., Cascio, K., Poll S., Darwiche, A., & Uchuk, S. (2010). Probabilistic model-based diagnosis: an electrical system case study, *IEEE Trans. System, Man, and Cybernetics – Part A: Systems and Humans*, 40(5): 874-885. ISSN 1083-4427

[12] Prasannamoorthy, V. & Devarajan, N. (2011). Fault detection and classification in power electronic circuits using wavelet transform and neural network, *Journal of Computer Science*, 7(1): 95-100. ISSN: 1549-3636

[13] Simani, S., Fantuzzi, C. & Patton, R. (2002). *Model-based fault diagnosis in dynamic systems using identification techniques*, Springer-Verlag, ISBN 978-1852336851, New York

[14] Spina, R. & Upadhyaya, S. (1997). Linear Circuit Fault Diagnosis Using Neuromorphic Analyzers. *IEEE Trans. Circuits and Systems*, 44(3): 188–196. ISSN 1057-7130

[15] Shumsky, A. (2009). Functional diagnosis of nonlonear time-delay dynamic systems, *Automation and Remote Control*, 70(3): 172-184. ISSN 0005-1179

[16] Shumsky A. Data driven method for fault detection and isolation in nonlinear uncertain systems // CD-ROM *Proc. IFAC Conf. on Control Applications in Marine Systems*, 2007

[17] Zhirabok, A. (2008). Nonlinear parity relation: logic-dynamic approach, *Automation and Remote Control*, 69(6): 1051-1064. ISSN 0005-1179

[18] Zhirabok A. & Tkachev D. (2010). Method of fault isolation in electrical circuits, *Proc. 15th Int. Conf. Methods and Models in Automation and Robotics*. Miedzyzdroje, Poland. 308-312

[19] Zhirabok A. & Tkachev D. (2011). Method of fault detection and isolation in nonlinear electrical circuits, *Proc. of Int. Conference "Advances in Safety, Reliability and Risk Management*", Troyes, France, 470-477. ISBN 978-0-415-68379-1

[20] Zhirabok, A. & Usoltsev, S. (2002). Fault diagnosis for nonlinear dynamic systems via linear methods. *CD ROM Proc. of the 15th World Congress IFAC*, Spain, 2002