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模拟电路的故障度量化算法

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摘要: 提出了一种可以评价模拟电路工作状态的故障度量化算法. 因为模拟电路里存在一些模糊量, 本文将模拟电路视为模糊系统. 提出了基于模糊隶属函数的故障度量化函数, 并与决策函数相结合构成了模拟电路故障度量化算法. 对模拟电路的故障程度进行精确量化, 有助于模拟电路故障诊断和故障修复. 故障度量化算法可以计算模拟电路的全局故障度, 从而准确地、客观地评价模拟电路的故障水平.

关键词: 模拟电路; 故障度; 隶属函数; 模糊理论
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A fuzzy quantifying algorithm of fault-degree in analog circuits

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Abstract: A quantifying algorithm of fault-degree is proposed to evaluate the working state of analog circuits. Because there are a lot of fuzzy physical quantities in analog circuits, analog circuits are regarded as a fuzzy system. The fault-degree quantifying functions are proposed based on fuzzy membership functions. These functions and the decision function are combined to constitute the quantifying algorithm for determining the fault-degree in analog circuits. Accurately quantifying the fault-degree is helpful to fault diagnosis and fault recovery of analog circuits. The fault level of analog circuits can be evaluated by the global fault-degree accurately and objectively.

Key words: analog circuit; fault-degree; membership function; fuzzy theory

1 Introduction

Fault diagnosis[1–2] of analog circuits is very important in electronics research. In recent years, scientists have gotten a great deal of research progress in fault diagnosis of analog circuit. Now the research centre and achievement of analog circuits fault diagnosis are focusing on classification method[3–4] and feature extraction, the research about evaluating the working state of analog circuits is less. Accurate quantifying the fault degree of analog circuits is helpful to evaluate the working state of analog circuits, and could judge whether analog circuits need be diagnosed or repaired.

There are some fuzzy physical quantities in analog circuits, such as the fault degree of analog components or circuits with tolerance[5–6], the stability[7] of analog circuits and fault feature[8] of analog circuits. Because there is the tolerance in analog components[9–10] and input signal, it is very difficult to quantify the fault degree and diagnose fault. The study object of fuzzy theory[11–12] is the ambiguous thing. Fuzzy sets[13] and membership function[14–15] are the mathematical foundations of fuzzy theory. Fuzzy object can be accurately described by fuzzy theory.

Analog circuits are regarded as a fuzzy system in this paper. A quantifying algorithm of fault degree is proposed to evaluate the working state of analog circuits. The fault degree quantifying functions based on fuzzy membership functions are set up. The fault degree quantifying functions and the decision function are combined to the quantifying algorithm of analog circuits fault degree. The fault level of analog circuits can be evaluated by the fault degree index accurately and objectively.

2 Fuzzy sets and membership function

In domain U, x is an element of U, $\forall x \in U$. A is a fuzzy subset of U. The membership between x and A is ambiguous. $\mu_{\rm A}$ is the membership function that describes the membership between element x and subset A. $\mu_{\rm A}(x)$ is the membership degree between element x and subset A, $0\leqslant \mu_{\rm A}(x) \leqslant 1$. The greater $\mu_{\rm A}(x)$ is, the greater membership between x and A is. There are several membership functions according to the various fuzzy systems. Four familiar membership functions are shown in Fig.1.

In Figs.1(a)(c) and (d) are symmetrical curves. At the centers a of these curves, the membership degree between element x and subset A is the maximum, $\mu_{\rm A}(x) = 1$. The membership degree decreases gradually when x deviates from a. The membership degree between x and A is the minimum when the distance between x and a is big enough, $\mu_{\rm A}(x) = 0$.

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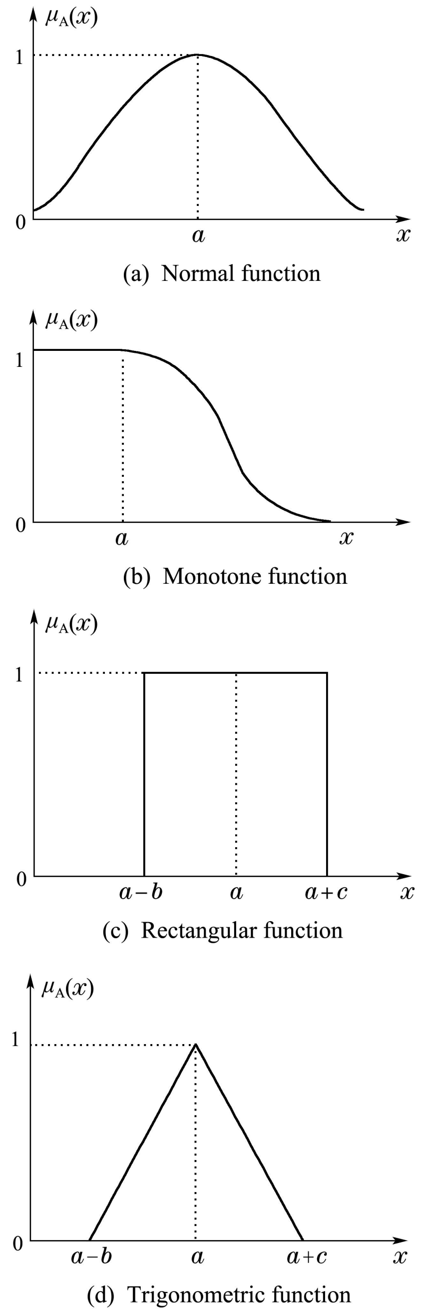

(a) Normal function

(b) Monotone function

(c) Rectangular function

(d) Trigonometric function

Fig. 1 Curves of membership functions

Membership function of normal distribution has two types: convex curve and concave curve. Convex curve of normal distribution[16] is shown in Fig.1(a). Its membership function is shown as Eq.(1):

$$\mu_{\mathrm{A}}(x)=\mathrm{e}^{-k(x-a)^2}. \tag{1}$$

Membership function of monotone curve has two types: monotone increasing curve and monotone decreasing curve. The membership function of Fig.1(b) monotone decreasing curve is shown as Eq.(2):

$$\mu_{\mathrm{A}}(x)=\begin{cases}1, & x\leqslant a,\\ \mathrm{e}^{-k(x-a)^2}, & x\geqslant a.\end{cases} \tag{2}$$

Convex rectangular polyline is shown in Fig.1(c). Its membership function is shown as Eq.(3).

$$\mu_{\mathrm{A}}(x)=\begin{cases}0,\ x\leqslant a-b;\ x\geqslant a+c,\\ 1,\ a-b\leqslant x\leqslant a+c.\end{cases} \tag{3}$$

The membership functions of trigonometric polylines have two types: direct trigonometric polyline and inverted trigonometric polyline. The membership function of Fig.1(d) direct trigonometric polyline is shown as Eq.(4):

$$\mu_{\mathrm{A}}(x)=\begin{cases}0, & x\leqslant a-b;\ x\geqslant a+c,\\ \dfrac{x-a+b}{b}, & a-b\leqslant x\leqslant a,\\ \dfrac{a+c-x}{c}, & a\leqslant x\leqslant a+c.\end{cases} \tag{4}$$

3 Quantifying algorithm of fault degree

3.1 Fault degree index of analog circuits

The fault level of analog circuits and analog components is fuzzy. Some fuzzy words are used to describe the fault degree of analog circuits, such as serious fault, general fault or slight fault. The fault level of analog circuits can be evaluated by the fault degree index accurately in this paper. The fault degree index is 0 when there is no fault in analog circuits. The fault degree index will increase when the circuits parameters drift from standard value. The fault degree index is 100% when analog circuits breakdown thoroughly.

A quantifying algorithm is proposed to evaluate the fault degree of analog circuits in this section. The fault degree quantifying functions based on fuzzy membership functions are set up. The fault degree quantifying functions and the decision function are combined to the quantifying algorithm of analog circuits fault degree. Firstly, the fault degree quantifying functions are used to get the local fault degree of every testing point[17] in analog circuit. Secondly, the decision function is used to synthesize all the local fault degree to the global fault degree of analog circuit.

3.2 Quantifying functions of fault degree

Several typical quantifying functions of analog circuits fault degree are proposed in this section. Curves of fault degree are the approximate expression of analog circuits fault degree. According to various analog circuits, there are several curves of fault degree. Three familiar curves of fault degree are shown in Fig.2.

In Fig.2, all fault degree curves are symmetrical curves. Horizontal axis is the parameters of analog components or circuits. Vertical axis is the fault degree of analog components or circuits. At the centers of these curves, analog components or circuits work in the ideal state, the fault degree is 0, $f(a)=0$. The fault degree increases gradually when the parameters of analog components or circuits deviate from the ideal value. The fault degree is 100% when the parameters are beyond the ultimate range, $f(x)=100\%$.

Fuzzy membership functions are transformed to the quantifying functions of fault degree. According to three fault degree curves in Fig.2, three quantifying functions of fault degree are shown as Eqs.(5)–(7).

Normal fault degree quantifying function:

$$f(x)=[1-\mathrm{e}^{-k(x-a)^2}]\times 100\%. \tag{5}$$

Rectangular fault degree quantifying function:

$$f(x) = \begin{cases} 100\%, & x \leqslant a;\ x \geqslant b, \\ 0, & a \leqslant x \leqslant b. \end{cases} \tag{6}$$

Trigonometric fault degree quantifying function:

$$f(x)=\begin{cases} 100\%, & x\leqslant a-b;\ x\geqslant a+b, \\ \dfrac{a-x}{b}\times 100\%, & a-b\leqslant x\leqslant a, \\ \dfrac{x-a}{c}\times 100\%, & a\leqslant x\leqslant a+c. \end{cases} \tag{7}$$

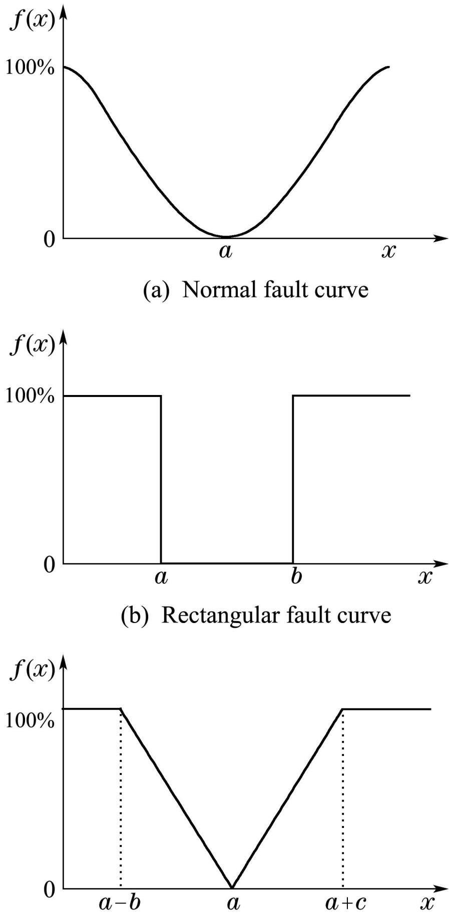

Fig. 2 Three familiar fault degree curves

The different quantifying function of fault degree should be selected to quantify the fault degree according to the specific analog component or analog circuit. Normal fault degree quantifying function can be selected to quantify the fault degree of analog component or analog circuit with tolerance. In Fig.2(a), the bottom of normal fault degree curve is flat. The fault degree is 0 approximately when the actual parameter is in the tolerant range. The fault degree increases rapidly when the deviation between the actual parameter and the ideal value is beyond the tolerant range. Trigonometric fault degree curve can be regarded as the approximate expression of normal fault degree curve. Rectangular fault degree quantifying function can be selected to quantify the fault degree of analog comparator, relay and digital circuit. The state of these circuits is unchanged when the signal changes within limits; the fault degree is 0. The state of these circuits will turn thoroughly when the signal changes without limits; the fault degree is 100%.

There are two parameters in Eq.(5), a and k. parameter a is the center of normal fault degree curve, the ideal value or the standard value of analog component or circuit. Parameter a can be gotten by simulation, theory or actual measurement. Parameter k is the gathered degree of normal fault degree curve. Parameter k can be gotten by the following steps: the working scope of analog component or circuit is analyzed; the fault degree is 0 when the actual value x is a; the fault degree is assumed to be 99% when the actual value x is the maximum value or the minimum value:

$$f(x) = \begin{cases} 0, & x = a, \\ 1 - \mathrm{e}^{-k(x-a)^2}, & x \text{ is in working scope}, \\ 99\%, & x \text{ is the limit of working scope}, \\ 1, & x \text{ is beyond the limit of working scope}. \end{cases} \tag{8}$$

3.3 Decision function of global fault degree

A quantifying function of fault degree only can calculate a local fault degree at a testing point of analog circuit. The decision function[18] is used to synthesize all the local fault degree to the global fault degree of the whole analog circuit after all local fault degree indexes of every testing point are gotten.

There are n testing points in an analog circuit. f_j is a local fault degree at the testing point j. All local fault degree is $(f_1, f_2, \cdots, f_n)$. Because the position of every testing point is different, the weight of every testing point is different during quantifying the fault degree of analog circuit. w_j is the weight of a testing point. All weight is $(w_1, w_2, \cdots, w_n)$. $0 \leqslant w_j \leqslant 1$ and $\sum\limits_{j=1}^{n} w_j = 1$. The decision function of global fault degree is shown as Eq.(9). F is the global fault degree of the whole analog circuit.

$$F = \sum_{j=1}^{n} (w_j \cdot f_j). \tag{9}$$

4 Example

4.1 An analog circuit and measured data

An analog circuit of controlling relay is shown in Fig.3. The model of the electromagnetic relay is EDR201A05. The relay switches into conduction when input DC voltage is more than 5 V. The resistance of coil is 500 Ω when the relay conducts. The relay J is used to control lamp L. Lamp L can light for a while after switch K is pressed by pedestrian.

There are three testing points in Fig.3. Measured data of three testing points are collected when the switch K is closed stably: the voltage U_{b} of the base of the transistor T at the testing point 1, the voltage U_{c} of the collector of the transistor T at the testing point 2 and the status of lamp L at the testing point 3.

Five states of analog circuit are randomly simulated to be the samples of fault degree quantifying algorithm. These states may be normal working state or random fault state, such as resistor failure, capacitor failure, transistor failure, relay failure, et al. Measured data of 5 states are shown in Table 1. Because this paper only quantifies the fault degree of analog circuit, fault type of every state is not listed in Table 1.

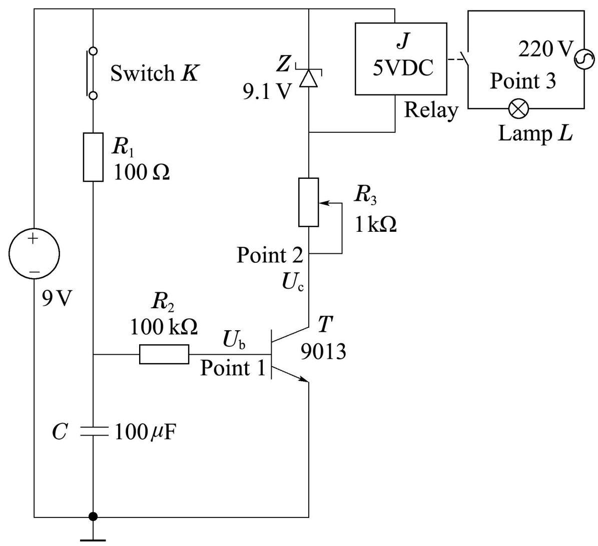

Fig. 3 Analog circuit

Table 1 Five samples of fault degree quantification

State	U_b/V	U_c/V	L
1	0.717	1.459	1
2	0.686	2.824	1
3	0.001	8.998	0
4	0.703	3.375	0
5	0.655	0.366	0

4.2 Fault curves and quantifying functions

In order to build the fault degree curves and quantifying functions of analog circuit, the center and the working scope of every testing point need be analyzed to select the optimal functions and parameters. Firstly, the ideal state of analog circuit is analyzed. The base-emitter (BE) junction of the transistor is forward-biased and the base-collector (BC) junction is reverse-biased when the switch K is closed stably. The ideal voltage of the base of the transistor at the testing point 1 is 0.7 V. Potentiometer R_3 is adjusted to make the voltage of the collector of the transistor at the testing point 2 is 2.5 V. The relay J is closed and the lamp L is light. The centers and the ideal value of three testing points is

$$U_b = 0.7\,\mathrm{V},\ U_c = 2.5\,\mathrm{V},\ L = 1.$$

If U_b< 0.5 V, the BE junction of the transistor will be cut off. If U_b> 0.9V, the BE junction will be punctured. So the working scope of the base of the transistor T at the testing point 1 is: 0.5 V <U_b< 0.9 V. Normal fault degree quantifying function is selected. Normal fault degree curve of U_b is shown in Fig.4. The fault degree $f(U_b) = 0$ when $U_b = 0.7$ V; the fault degree $f(U_b) = 99\%$ when $U_b = 0.5$ V or 0.9 V. These data are plugged into Eq.(5) to solve a and k. The fault degree quantifying function of U_b is shown as Eq.(10):

$$f(U_b) = [1 - \mathrm{e}^{-115.13\times(U_b-0.7)^2}] \times 100\%\ . \quad (10)$$

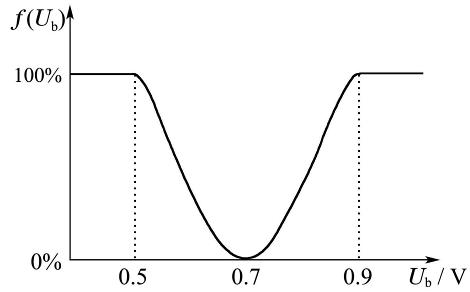

Fig. 4 Normal fault degree curve of U_b

The voltage of the collector-emitter (CE) is about 0.3 V when the transistor T works in the deep saturation mode. The relay J will be cut off if $U_c > 4.7$ V. So the working scope of the collector of the transistor T at the testing point 2 is: 0.3 V< U_c <4.7 V. Normal fault degree quantifying function is selected. Normal fault degree curve of U_c is shown in Fig.5. The fault degree $f(U_c) = 0$ when U_c = 2.5V; the fault degree $f(U_c) = 99\%$ when $U_c = 0.3$ V or 4.7 V. These data are plugged into Eq.(5) to solve a and k. The fault degree quantifying function of U_c is shown as Eq.(11):

$$f(U_c) = [1 - \mathrm{e}^{-0.9515\times(U_c-2.5)^2}] \times 100\%\ . \quad (11)$$

Because lamp L only have two modes: luminous and nonluminous, rectangular fault degree quantifying function is selected. Rectangular fault degree curve of L is shown in Fig.6. The fault degree $f(L)$ = 0 when the lamp L is luminous, L = 1; the fault degree $f(L)$ = 100% when the lamp L is dark, L = 0. The fault degree quantifying function of L is shown as Eq.(12):

$$f(L) = \begin{cases} 0\%, & L = 0, \\ 100\%, & L = 1. \end{cases} \quad (12)$$

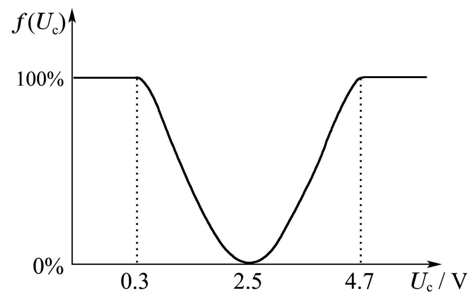

Fig. 5 Normal fault degree curve of U_c

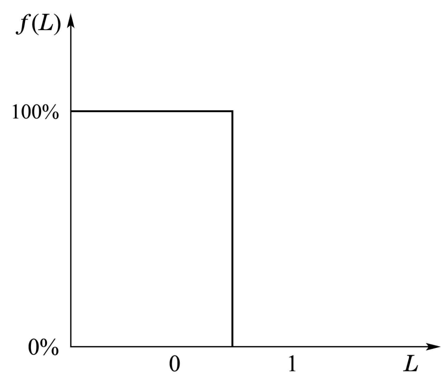

Fig. 6 Rectangular fault degree curve of L

4.3 Calculation of fault degree

The data of Table 1 are plugged into Eqs.(10)–(12) to calculate the local fault degree at every testing point. The local fault degree is shown in Table 2.

Table 2 Local fault degree

State	$f(U_{\rm b})$/%	$f(U_{\rm c})$/%	$f(L)$/%
1	3.27	64.34	0
2	2.23	9.51	0
3	100	100	100
4	0.1	51.74	100
5	20.8	98.69	100

Matrix M of the local fault degree is built as the follows. In matrix M, f_{ij} is the local fault degree of the circuit state i at the testing point j.

$$M = \begin{bmatrix} f_{11} & f_{12} & f_{13} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \\ f_{41} & f_{42} & f_{43} \\ f_{51} & f_{52} & f_{53} \end{bmatrix} = \begin{bmatrix} 0.0327 & 0.6434 & 0.0 \\ 0.0223 & 0.0951 & 0.0 \\ 1.0000 & 1.0000 & 1.0 \\ 0.0010 & 0.5174 & 1.0 \\ 0.2080 & 0.9869 & 1.0 \end{bmatrix}.$$

The decision function is used to synthesize several the local fault degrees to the global fault degree of every circuit state. Because the weight of every testing point is different during quantifying the fault degree, the weight vector (w_1, w_2, w_3) of Eq.(9) must be set.

The status of lamp L is the most obvious and the most important in analog circuit, so the weight of the testing point 3 is promoted to $w_3 = 0.5$. Whether the relay J can be closed depends on the voltage of the collector of the transistor T, so the weight of the testing point 2 is set to $w_2 = 0.3$. The weight of the voltage of the base of the transistor T is the smallest. The weight of the testing point 1 w_1 is set to 0.2 to make the total of all weight is 1. So the weight of every testing point is

$$w_1 = 0.2,\ w_2 = 0.3,\ w_3 = 0.5.$$

The data of Table 2 and the weight of every testing point are plugged into Eq.(9). The global fault degree of every circuit state is calculated by the decision function, the result is shown in Table 3.

Table 3 Global fault degree of every circuit state

State	Fault degree/%
1	$F_1 = 19.96$
2	$F_2 = 3.30$
3	$F_3 = 100$
4	$F_4 = 65.54$
5	$F_5 = 83.77$

4.4 Result of fault degree quantifying

According to Table 3, the histogram of the global fault degree of every circuit state is shown in Fig.7.

After Fig.7 and Table 3 are analyzed, some helpful results can be summarized as follows:

1) The rank order of fault degree of 5 circuit states is: $F_3 > F_5 > F_4 > F_1 > F_2$. The fault degree is the accurate numerical description of the fault level of analog circuit. The greater the fault degree is, the worse the working state of analog circuit is.

2) The fault degree of the third circuit state is 100%. It means that the third circuit breakdown thoroughly, the third circuit need be repaired. In the third sample of Table 1, all parameters deviate from the working scope completely. The transistor T is closed; the relay J is open; the lamp L is not light. There may be the following fault: the switch K is cut off, the resistor R_1 is open-circuited, the capacitor C is short-circuited, the resistor R_2 is open-circuited, the BE junction of the transistor T is short-circuited, et al.

3) The fault degree of the second circuit state is 3.30%. It means that the working state of the second circuit is perfect. Because there is tolerance in analog components and analog circuits, the small distance between the actual parameters and the ideal value is right.

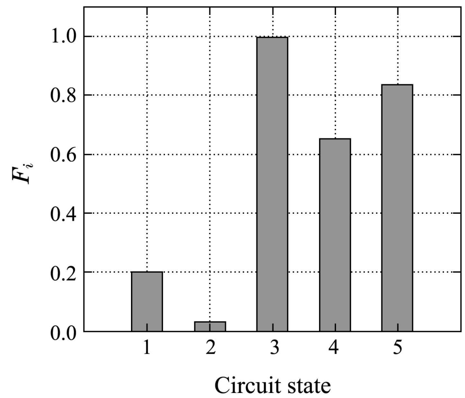

Fig. 7 Global fault degree of every circuit state

5 Conclusions

Accurate quantifying the fault degree is helpful to fault diagnosis and fault recovery of analog circuits. Analog circuits can be regarded as a fuzzy system because there are a lot of fuzzy physical quantities in analog circuits. A quantifying algorithm of fault degree is proposed to describe the working condition of analog circuits. Several fault degree quantifying functions are proposed based on fuzzy membership functions. The fault degree quantifying functions and the decision function are combined to the quantifying algorithm of fault degree in analog circuits. Firstly, the fault degree quantifying functions are used to get the local fault degree of every testing point in analog circuit. Secondly, the decision function is used to synthesize all the local fault degree to the global fault degree of analog circuit. Finally, the fault level of analog circuits can be evaluated by the global fault degree exactly.

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