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MULTI ELEMENT FAULT ISOLATION IN ELECTRONIC CIRCUITS

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ABSTRACT

A method is developed for the identification of the each of the faulty elements in the linear Electronic Circuits when one or more of the elements are simultaneously off from their nominal value. Exact analytical expressions are presented for the identification of one and two simultaneously faulty elements, along with the algorithm for the multiple faulty elements case. In general for an m element fault, 2^{m-1} different measurements are made (real and imaginary part). These measurements may involve transfer function frequency response at 2^{m-1} different frequencies, or in case of degeneracy, different functions such as input inpedances, etc., such that total different measurements are 2^{m-1}. Method is discussed by means of examples.

1. INTRODUCTION

A method of fault isolation in the linear circuits for a single faulty element has been proposed by Martens and Dyck[1] and others[2]-[3] using bilinear transformation. The method is graphical in nature, producing frequency domain loci which depend upon the value of the assumed faulty element. The faulty element is identified by the location of the test measurements of the equipment on a particular loci. Besides having the limitation of being applicable to a single element fault only, the method is cumbersome for automatic computer mechanization. In this paper we present analytical expression for the identification of one or two faulty elements and derive a general algorithm for the multi elements fault case. We shall assume that the symbolic transfer dunctions (or different transfer functions between different sets of terminals) is known[4]-[6]. The method of fault identification is explained by means of examples.

2. PROBLEM STATEMENT AND ASSUMPTIONS

The problem proposed consists in isolating faulty elements (one or more) in a lumped, linear time invariant, active electronic networks. It is assumed that the topology of the network and the nominal value of the components are known, so that the symbolic transfer function can be obtained. It is futher assumed that failures are not catastrophic and enough test terminals are available to obtain frequency response which is dependent on the value of elements which are faulty.

3. METHOD OF SOLUTION

3.1 Single faulty element

Let the various elements such as transistors, resistors etc. of the network be symbolized by $p_1, p_2, \dots, p_n$, n being the total number of elements. The nominal value of these elements be given by $p_{10}, p_{20}, \dots, p_{no}$.

Let

$$0 < \frac{p_i}{p_{10}} = x_i, \quad i=1,\dots,n \qquad 3.1.1$$

When all x_i, $(i=1,\dots,n)$ are unity, the equipments is not faulty.

Let us consider the situation when a particular k^{th} component is faulty, such that $x_k \neq 1$. Problem reduces to determining all different x's and thus the faulty element and its value. The system transfer function T(s) can be written in n different forms[7] as

$$T(s) = T(s,x_k) = \frac{A_k(s)\ x_k + B_k(s)}{C_k(s)\ x_k + D_k(s)}, \quad (k=1,\dots,n) \qquad 3.1.2$$

Let us obtain the frequency of this equipment at one particular frequency ω, involving phase and amplitude measurement and hence the real $R(\omega)$ and imaginary part $X(\omega)$, yielding

$$T(j\omega) = R(\omega) + jX(\omega) = \frac{A_k(j\omega)\ x_k + B_k(j\omega)}{C_k(j\omega)\ x_k + D_k(j\omega)}, \quad (k=1,\dots,n) \qquad 3.1.3$$

The test frequency is choosen with regard to the nominal poles and zeros locations, as discussed by Seshu and Waxman[8].

Let

$$\begin{aligned} A_k(j\omega) &= A_{k_1}(\omega) + jA_{k_2}(\omega) \\ B_k(j\omega) &= B_{k1}(\omega) + jB_{k_2}(\omega) \\ C_k(j\omega) &= C_{k_1}(\omega) + jC_{k_2}(\omega) \\ D_k(j\omega) &= D_{k_1}(\omega) + jD_{k_2}(\omega) \end{aligned} \qquad 3.1.4$$

Substituting 3.1.4 into 3.1.3 and equating real and imaginary part,

$$
\begin{aligned}
&(R(\omega)C_{k_1}(\omega)-X(\omega)C_{k_2}(\omega))x_k + (R(\omega)D_{k_1}(\omega)-X(\omega)D_{k_2}(\omega)) \\
&\qquad = A_{k_1}(\omega)x_k + B_{k_1}(\omega) \\
&(R(\omega)C_{k_2}(\omega)+X(\omega)C_{k_1}(\omega))x_k + (R(\omega)D_{k_2}(\omega)+X(\omega)D_{k_1}(\omega)) \\
&\qquad = A_{k_2}(\omega)x_k + B_{k_2}(\omega)
\end{aligned}
\qquad 3.1.5
$$

The relations 3.1.5 are true only when k^{th} element symbolized by x_k is the faulty element. The quantities $A_{k_1}(\omega)$ etc. are computed for the nominal values of other elements (except of course the k^{th} element). Since both the equations of 3.1.5 should give the same value of x_k, the condition that k^{th} element is indeed the faulty one is given by eliminating x_k from equations 3.1.5 to yield.

$$
\begin{aligned}
&(X^2(\omega)+R^2(\omega))(C_{k_1}(\omega)D_{k_2}(\omega)-C_{k_2}(\omega)D_{k_1}(\omega)) + \\
&\quad + R(\omega)(D_{k_1}(\omega)A_{k_2}(\omega)+C_{k_2}(\omega)B_{k_1}(\omega)-D_{k_2}(\omega)A_{k_1}(\omega)-C_{k_1}(\omega)B_{k_2}(\omega)) \\
&\quad + X(\omega)(C_{k_1}(\omega)B_{k_1}(\omega)+C_{k_2}(\omega)B_{k_2}(\omega)-D_{k_1}(\omega)A_{k_1}(\omega)-D_{k_2}(\omega)A_{k_2}(\omega)) \\
&\quad + (A_{k_1}(\omega)B_{k_2}(\omega)-A_{k_2}(\omega)B_{k_1}(\omega) = \Delta_k(\omega) = 0
\end{aligned}
\qquad 3.1.6
$$

Theoretically only frequency measurement at one frequency is necessary, but due to noise consideration, the condition 3.1.6 may be verified at different frequencies. If

$$\frac{1}{m}\sum_{i=1}^{m} \Delta^2{}_k(\omega_i)$$

is less than some precomputed number ϵ, then the condition

3.1.6 is considered fulfilled. Furthermore value of x_k should be positive.

3.2 Example

Consider simple circuit given in Figure 3.2.1

Let the nominal values of these various elements be

$$\begin{aligned} R_1 &= R_{10} = 1000\ \mathrm{K}\Omega \\ C &= C_0 = 1\ \mu\mathrm{F} = 10^{-6}\mathrm{F} \\ R_2 &= R_{20} = 3000\ \mathrm{K}\Omega \end{aligned} \qquad 3.2.1$$

The actual values of these elements are such that the frequency response $\left[\dfrac{u_2(s)}{u_1(s)}\right]$ at $\omega=1$ is

$$\begin{aligned} R(\omega) &= \frac{11}{26} \\ X(\omega) &= -\frac{3}{26} \end{aligned} \qquad 3.2.2$$

Only one element is considered off from the nominal value. We are required to find this element and its value.

Let

$$\frac{R_1}{R_{10}} = x_1, \quad \frac{R_2}{R_{20}} = x_2, \quad \frac{C}{C_0} = x_3 \qquad 3.2.3$$

$$T(s) = \frac{u_2(s)}{u_1(s)} = \frac{1 + Sc\,R_1}{1 + Sc(R_1+R_2)} = \frac{A(s)x + B(s)}{C(s)x + D(s)} \qquad 3.2.4$$

Thus

$$T(s,x_1) = T_1(s) = \frac{1+SC_0R_{10}x_1}{1+SC_0(R_{10}x_1+R_{20})} \qquad 3.2.5$$

$$T(s,x_2) = T_2(s) = \frac{1+SC_0R_{10}}{1+SC_0(R_{10}+R_{20}x_2)} \qquad 3.2.6$$

$$T(s,x_3) = T_3(s) = \frac{1+SC_0R_{10}x_3}{1+SC_0(R_{10}+R_{20})x_3} \qquad 3.2.7$$

$A_{11}(\omega)= 0$	$A_{21}(\omega)= 0$	$A_{31}(\omega)= 0$
$A_{12}(\omega)= \omega C_0R_{10}=1$	$A_{22}(\omega)= 0$	$A_{32}(\omega)= \omega C_0R_{10}=1$
$B_{11}(\omega)= 1$	$B_{21}(\omega)= 1$	$B_{31}(\omega)= 1$
$B_{12}(\omega)= 0$	$B_{22}(\omega)= \omega C_0R_{10}=1$	$B_{32}(\omega)= 0$
$C_{11}(\omega)= 0$	$C_{21}(\omega)= 0$	$C_{31}(\omega)= 0$
$C_{12}(\omega)= \omega C_0R_{10}=1$	$C_{22}(\omega)= \omega C_0R_{20}=3$	$C_{32}(\omega)= \omega C_0(R_{10}+R_{20})=4$
$D_{11}(\omega)= 1$	$D_{21}(\omega)= 1$	$D_{31}(\omega)= 1$
$D_{12}(\omega)= \omega C_0R_{20}=3$	$D_{22}(\omega)= \omega C_0R_{10}=1$	$D_{32}(\omega)= 0$

Substituting these values in 3.1.6, we obtain

$$\Delta_1 = \frac{130}{(26)^2}(-1) + \frac{11}{26}(2) - \frac{3}{26}(-3) - 1 = 0 \qquad 3.2.8$$

$$\Delta_2 = \frac{130}{(26)^2}(-3) + \frac{11}{26}(3) - \frac{3}{26}(3) = \frac{4}{13} \qquad 3.2.9$$

$$\Delta_3 = \frac{130}{(26)^2}(-4) + \frac{11}{26}(5) - \frac{3}{26}(0) - 1 = \frac{9}{26} \qquad 3.2.10$$

Thus element R_1 is faulty and its value is obtained as

$$x_1 = x_k = \frac{B_{k_1}(\omega)-R(\omega)D_{k_1}(\omega)+X(\omega)D_{k_2}(\omega)}{R(\omega)C_{k_1}(\omega)-X(\omega)C_{k_2}(\omega)-A_{k_1}(\omega)} =$$

$$= \left(\frac{26-20}{26}\right)\left(\frac{26}{3}\right) = 2 \qquad 3.2.11$$

Hence actual value of R_1 is 2000 K.

When none of the determinants $\Delta_k(\omega)$ are zero, then their is more than one element which is faulty. In case of degeneracy such function such as input impedance is used for identification[9].

3.3 Fault with two faulty elements

Let k_1 and k_2 be two faulty elements symbolized by x_{k_1} and x_{k_2} respectively. The transfer function can be written as

$$T(s) = T(s,k_1,k_2) =$$

$$= \frac{A_{k_1,k_2}(s)\, x_{k_1}\, x_{k_2} + B_{k_1,k_2}(s)\, x_{k_1} + C_{k_1,k_2}(s)\, x_{k_2} + D_{k_1,k_2}(s)}{E_{k_1,k_2}(s)\, x_{k_1}\, x_{k_2} + F_{k_1,k_2}(s)\, x_{k_1} + G_{k_1,k_2}(s)\, x_{k_2} + H_{k_1,k_2}(s)}$$

where $A_{k_1,k_2}(s)$ etc. are polynomials in s.

Let $A_{k_1,k_2}(j\omega) = A_1(\omega) + j\, A_2(\omega)$ etc. dropping the indices k_1,k_2 for convenience

$$T(j\omega) = R(\omega) + j\,X(\omega)$$

The real and imaginary part of 3.3.1 can yield the following two equations.

$$[R(\omega)E_1(\omega)-X(\omega)E_2(\omega)-A_1(\omega)]x_{k_1}x_{k_2} +$$
$$+ [R(\omega)F_1(\omega)-X(\omega)F_2(\omega)-B_1(\omega)]x_{k_1} +$$
$$+ [R(\omega)G_1(\omega)-X(\omega)G_2(\omega)-C_1(\omega)]x_{k_2} + \qquad 3.3.2$$
$$+ [R(\omega)H_1(\omega)-X(\omega)H_2(\omega)-D_1(\omega)] = 0$$

$$[R(\omega)E_2(\omega)+X(\omega)E_1(\omega)-A_2(\omega)]x_{k_1}x_{k_2} +$$
$$+ [R(\omega)F_2(\omega)+X(\omega)F_1(\omega)-B_2(\omega)]x_{k_1} +$$
$$+ [R(\omega)G_2(\omega)+X(\omega)G_1(\omega)-C_2(\omega)]x_{k_2} + \qquad 3.3.3$$
$$+ [R(\omega)H_2(\omega)+X(\omega)H_1(\omega)-D_2(\omega)] = 0$$

These equations can be rewritten as

$$P(\omega)x_{k_1}x_{k_2} + Q(\omega)x_{k_1} + U(\omega)x_{k_2} + V(\omega) = 0 \qquad 3.3.4$$

$$K(\omega)x_{k_1}x_{k_2} + L(\omega)x_{k_1} + M(\omega)x_{k_2} + N(\omega) = 0 \qquad 3.3.5$$

where

$$P(\omega) = R(\omega)E_1(\omega) - X(\omega)E_2(\omega) - A_1(\omega)$$
$$Q(\omega) = R(\omega)F_1(\omega) - X(\omega)F_2(\omega) - B_1(\omega)$$
$$U(\omega) = R(\omega)G_1(\omega) - X(\omega)G_2(\omega) - C_1(\omega) \qquad 3.3.6$$

$$V(\omega) = R(\omega)H_1(\omega) - X(\omega)H_2(\omega) - D_1(\omega)$$
$$K(\omega) = R(\omega)E_2(\omega) + X(\omega)E_1(\omega) - A_2(\omega)$$
$$L(\omega) = R(\omega)F_2(\omega) + X(\omega)F_1(\omega) - B_2(\omega)$$
$$M(\omega) = R(\omega)G_2(\omega) + X(\omega)G_1(\omega) - C_2(\omega)$$
$$N(\omega) = R(\omega)H_2(\omega) + X(\omega)H_1(\omega) - D_2(\omega) \qquad 3.3.6$$

Let us now perform the frequency response test at two different frequencies ω_1 and ω_2 yielding $R(\omega_1) + j\,(\omega_1)$ and $R(\omega_2) + jX(\omega_2)$. Substituting these in 3.3.6

$$P(\omega)|_{\omega = \omega_1} = p_1 \qquad \text{etc., we obtain}$$
$$P(\omega)|_{\omega = \omega_2} = p_2$$

$$p_1x_{k_1}x_{k_2} + q_1x_{k_1} + u_1x_{k_2} + v_1 = 0$$
$$k_1x_{k_1}x_{k_2} + \ell_1x_{k_1} + m_1x_{k_2} + n_1 = 0 \qquad 3.3.7$$
$$p_2x_{k_1}x_{k_2} + q_2x_{k_1} + u_2x_{k_2} + v_2 = 0$$
$$k_2x_{k_1}x_{k_2} + \ell_2x_{k_1} + m_2x_{k_2} + n_2 = 0$$

eliminating the product terms, these equations can be rewritten as

$$a_{11}x_{k_1} + a_{12}x_{k_2} + a_{13} = 0$$
$$a_{21}x_{k_1} + a_{22}x_{k_2} + a_{23} = 0 \qquad 3.3.8$$
$$a_{31}x_{k_1} + a_{32}x_{k_2} + a_{33} = 0$$

where

$$a_{11} = \frac{q_1}{p_1} - \frac{\ell_1}{k_1}, \quad a_{12} = \frac{u_1}{p_1} - \frac{m_1}{k_1}, \quad a_{13} = \frac{v_1}{p_1} - \frac{n_1}{k_1}$$

$$a_{21} = \frac{q_1}{p_1} - \frac{q_2}{p_2}, \quad a_{22} = \frac{u_1}{p_1} - \frac{u_2}{p_2}, \quad a_{23} = \frac{v_1}{p_1} - \frac{v_2}{p_2}$$

$$a_{31} = \frac{q_1}{p_1} - \frac{\ell_2}{k_2}, \quad a_{32} = \frac{u_1}{p_1} - \frac{m_2}{k_2}, \quad a_{33} = \frac{v_1}{p_1} - \frac{n_2}{k_2}$$

The condition that the k_1 and k_2 elements are faulty is given as

$$\begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} = \Delta_A = 0, \quad x_1 \geq 0,\ x_2 \geq 0 \qquad 3.3.9$$

When 3.3.9 is satisfies, the variables x_{k_1} and x_{k_2} can be solved from first two equation of 3.3.8. There are circuits where degeneracy occures and one transfer function alone is not sufficient to obtain the faulty elements In such a situation more than one functions are necessary to identify the faulty elements. Thus in case of example shown in Fig. 4.3.1, the first two equations of 3.3.7 are obtained by one function and the other two by another independent function.

Example of two faulty elements:

Consider the same example discussed in Fig.4.3.1. Two elements are assumed fault. At a frequency $\omega=1$, the transfer function frequency response and input admittance frequency response is given as

$$T(I) = \frac{13}{37} - j\,\frac{4}{37}, \quad Y(I) = \left(\frac{7}{37} - j\,\frac{5}{37}\right) 10^{-6}\ \mho \qquad 3.3.10$$

we are required to identify the faulty component. This is a degenerate network where different combinations of R_1, R_2 and C may yield the same transfer function. Hence two different functions are used for identification. Three different possible sets are:

$$T_{12}(s) = \frac{I+SC_{10}R_{10}x_1}{I+SC_{10}R_{10}x_1 + SC_{10}R_{20}x_2} = \frac{1 + Sx_1}{I+Sx_1+3Sx_2}$$

$$Y_{12}(s) = \frac{I + SC_O}{I+SC_OR_{10}x_1 + SC_OR_{20}x_2} = \frac{(1+S)}{1+Sx_1+3Sx_2}$$

R_1 and R_2 are faulty 3.3.11

$$T_{23}(s) = \frac{I+SR_{10}C_Ox_3}{I+SR_{10}C_Ox_3 + SR_{20}C_Ox_2x_3} = \frac{1+Sx_3}{I+Sx_3+3Sx_2x_3}$$

$$Y_{23}(s) = \frac{I + SC_Ox_3}{I+SR_{10}C_Ox_3 + SR_{20}C_Ox_2x_3} = \frac{1+Sx_3}{I+Sx_3+3Sx_2x_3}$$

R_2 and C are faulty 3.3.12

resistor R_1 and R_2 are the faulty components. Their true value is R_1=2000 K, R_2=4000 K.

Case 2. when R_2 and C are considered faulty.

From $T_{23}(s)$, A = B = O, C = j, D = I, E = 3j, F = O, G = j
H = I

$$P = \frac{12}{37}\ ,\ Q = 0,\ U = \frac{4}{37}\ ,\ V = -\frac{24}{37}$$

$$K = \frac{39}{37}\ ,\ L = 0,\ M = -\frac{24}{37}\ ,\ N = -\frac{4}{37}$$

The equations in variables x_2 and x_3 are

$$12x_2x_3 + 4x_3 = 24$$

$$39x_2x_3 - 24x_3 = 4$$

The solution is

$$x_3 = 2\ ,\ x_2 = 2/3$$

From $Y_{23}(s)$, which is same as $T_{23}(s)$

$$P = \frac{15}{37}\ ,\ Q = 0\ ,\ U = 5/37\ ,\ V = -\frac{30}{37}$$

$$K = \frac{21}{37}\ ,\ L = 0\ ,\ M = -\frac{30}{37}\ ,\ N = -\frac{5}{37}$$

The two equations for variables x_2 and x_3 are

$$15x_2x_3 + 5x_3 = 30$$

$$21x_2x_3 - 30x_3 = 5$$

yielding the solution $x_3=1$, $x_2=5/3$. Since this solution is not the same as obtained from $T_{23}(s)$, the elements R_2 and C are not the faulty elements as a pair.

Case 3. R_1 and C are considers faulty.

From $T_{31}(s)$, $A = j\omega,\ B = 0,\ C = 0,\ D = 1$,
$E = j\omega,\ F = 0,\ G = j3\omega,\ H = 1$

$$P = \frac{4}{37}\ ,\ Q = 0\ ,\ U = \frac{12}{37}\ ,\ V = -\frac{24}{37}\ ,$$

$$K = -\frac{24}{37}\ ,\ L = 0\ ,\ M = \frac{39}{37}\ ,\ N = -\frac{4}{37}\ .$$

The equations in x_1 and x_3, from the function $T_{31}(s)$ are:

$$x_1x_3 + 3x_3 = 6$$
$$-24x_1x_3 + 39x_3 = 4$$

Thus

$$x_1 = 3/2\ ,\quad x_3 = 4/3$$

From $Y_{31}(s)$, $A = B = 0,\ C = j\omega,\ D = 1\ ,\ E = j\omega$,
$F = 0,\ G = j3\omega,\ H = 1$

$$P = \frac{5}{37}\ ,\ Q = 0,\ U = \frac{15}{37}\ ,\ V = -\frac{30}{37}\ ,$$

$$K = \frac{7}{37}\ ,\ L = 0,\ M = -\frac{16}{37}\ ,\ N = -\frac{5}{37}$$

The equations in x_1 and x_3 from the function $Y_{31}(s)$ are

$$x_1x_3 + 3x_3 - 6 = 0$$
$$7x_1x_3 - 16x_3 - 5 = 0$$

yielding $x_1 = 3$, $x_3 = 1$.

The solution from $Y_{13}(s)$ and $T_{13}(s)$ do not agree with each other, concluding that R_1 and C are not the faulty pair. The conclusion reach is that R_1 and R_2 are the faulty resistors having actual value of 2000 K and 4000 K .

$$T_{31}(s) = \frac{I+SR_{10}C_O x_1 x_3}{I+SR_{10}C_O x_1 x_3 + SR_{20}C_O x_3} =$$

$$= \frac{1+Sx_3}{1+Sx_1x_3+3Sx_3}$$

$$Y_{31}(s) = \frac{1 + SC_O x_3}{I+SR_{10}C_O x_1 x_3 + SR_{20}C_O x_3} =$$

$$= \frac{1+Sx_3}{1+Sx_1x_3+3Sx_3}$$

R_1 and C are faulty 3.3.13

Case 1. R_1 and R_2 are considered faulty

From $T_{12}(s)$, $A = E = C = O$, $D = H = I$, $B = F = j$, $G = 3j$

$$P = K = O, \quad Q = \frac{4}{37}, \quad U = \frac{12}{37}, \quad V = \frac{24}{37}$$

$$L = \frac{24}{37}, \quad M = \frac{39}{37}, \quad N = \frac{4}{37}$$

The equations for variables x_1 and x_2, from the $T_{12}(s)$, are

$$x_1 + 3x_2 = 6$$

$$-24x_1 + 39x_2 = 4$$

The solution is given as $x_1=2$, $x_2=4/3$.

From $Y_{12}(s)$ $P = O$, $Q = 5/37$, $U = 15/37$, $V = -30/37$

$K = O$, $L = 7/37$, $M = 21/37$, $N = -212/37$

The two equations in variable x_1 and x_2 obtained from $Y_{12}(s)$ degenerate into one equation

$X_1 + 3x_2 = 6$, which is satisfied by the solution $x_1 = 2$ and $x_2 = 4/3$, confirming that indeed the resistor R_1 and R_2 are the faulty components. Their true

3.4 Fault with three or more simultaneously faulty elements

With three faulty elements to be simultaneously identified either we need four different function to measured at one frequency (real and imaginary part) or one function at four different frequencies (if no degeneracy occures). In general for a m element fault 2^{m-1} measurements (real and imaginary part) of different functions, or one function test at 2^{m-1} different frequencies is performed. For three element fault the equations obtained are of the form

$$a^{(i)}_{k_1k_2k_3}\, x_{k_1}x_{k_2}x_{k_3} + a^{(i)}_{k_1k_2}\, x_{k_1}x_{k_2} + a^{(i)}_{k_2k_3}\, x_{k_2}x_{k_3} + \\ + a^{(i)}_{k_3k_1}\, x_{k_3}x_{k_1} + a^{(i)}_{k_1} x_{k_1} + a_{k_2}\, x_{k_2} + \\ + a^{(i)}_{k_3} x_{k_3} + a^{(i)}_{0} = 0, \qquad 3.4.1$$

$$(i = 1,\dots,8)\ ,$$
$$(k_1 \neq k_2 \neq k_3\ ,\ k_1,k_2,k_3 = 1,\dots,n)$$

The product terms are eliminated by successive subtractions to obtain equations of the form

$$\begin{aligned} a_{11}x_{k_1} + a_{12}x_{k_2} + a_{13}x_{k_3} + a_{14} &= 0 \\ a_{21}x_{k_1} + a_{22}x_{k_2} + a_{23}x_{k_3} + a_{24} &= 0 \\ a_{31}x_{k_1} + a_{32}x_{k_2} + a_{33}x_{k_3} + a_{34} &= 0 \\ a_{41}x_{k_1} + a_{42}x_{k_2} + a_{43}x_{k_3} + a_{44} &= 0 \end{aligned} \qquad 3.4.2$$

The conditions that k_1, k_2 and k_3 are the faulty elements is given by

$$\Delta_A = \text{det of } A = 0,\ \underline{A} = \{a_{ij}\},\ (i,j=1,\dots,4) \qquad 3.4.3$$

$$x_{k_1} \geq 0, \quad x_{k_2} \geq 0, \quad x_{k_3} \geq 0 \qquad 3.4.4$$

The quanties x_{k_1}, x_{k_2}, x_{k_3} are solved from first three equations. The extension to m element fault is obvious.

4. CONCLUSION

A method has been presented for isolation of a fault when m elements are simultaneously faulty. In general 2^{m-1} different measurements real and imaginary part are made to identify the faulty elements. In case the transfer function alone can not identify the faulty components, other functions such as input impedance or transfer function between different sets of terminals is used. Method is suitable for automatic fault identification via digital computer.

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