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Single and multiple fault detection in combinational networks

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Abstract

This paper deals with a fault diagnosis technique for acyclic switching networks. For this purpose, two useful theorems are formulated and algorithms are described for generating the complete test sets for single as well as all possible multiple faults on any number of lines of the network. Illustrations showing the application of the theorems to fault diagnosis are also offered.

Key words: S-a-0 and S-a-1 faults, complete test set, single fault, multiple fault.

1. Introduction

Fault detection in combinational logic network is one of the principal areas of current research. Of a number of techniques[1–12] reported for the detection of fault in a combinational network, the techniques[1–9] based on the concept of boolean difference are attractive in the sense that they offer a direct analytical method of obtaining all test input patterns. But the implementation of these approaches requires the capability of manipulating boolean expressions.

The present paper reports on the development of a new technique to cater to single and multiple faults in a combinational network. Following this technique, it is only necessary to find the expressions of $f(X_i)$ and $\overline{f(X_i)}$ in the sum of product form when the single fault on any line i is under consideration. Similarly, to generate the complete test set for all possible multiple faults on any p lines $i_1, i_2, \ldots, i_p$ it is only necessary to find the expressions of $f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})$ and $\overline{f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})}$ in the sum of product form. Finally, the complete test set generation in the cases of both single and multiple fault has been reduced to finding the intersection of two sets $\{F_1\}$ and $\{F_2\}$ and as such the tedious steps of algebraic manipulation, manual labour and computation time required in the techniques[1–9] based on the concept of boolean difference can be easily dispensed with.

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2. Theorems

Theorem 1: If $f(x_1, x_2, \ldots, x_n)$ were a logical function realised by a combinational logic circuit, then the complete test set for single fault on any line i of the network is given by, $T(i) = \{F_1\} \bigcap \{F_2\}$,

where F_1 is the logical function obtained by taking the boolean sum of each product term of $f(X_i)$ disregarding X_i or $\bar{X}_i$ present in each of them, and F_2 is the logical function obtained by taking the boolean sum of each product term of $\overline{f(X_i)}$ disregarding X_i or $\bar{X}_i$ present in each of them.

Proof: The most general form of the function $f(x_1, x_2, \ldots, x_n)$ when expressed in terms of X_i is given by, $f(X_i) = g_1 X_i + g_2 \bar{X}_i + g_3$, where g_1, g_2 and g_3 are all functions of primary input variables.

$$\text{Now, } f(X_i) = g_1 X_i + g_2 \bar{X}_i + g_3(X_i + \bar{X}_i)$$
$$= (g_1 + g_3) X_i + (g_2 + g_3) \bar{X}_i$$
$$= f_1 X_i + f_2 \bar{X}_i, \text{ where } f_1 = g_1 + g_3, \quad f_2 = g_2 + g_3.$$

Hence, $F_1 = f_1 + f_2$,

$$\overline{f(X_i)} = \overline{f_1 X_i + f_2 \bar{X}_i} = (\bar{f}_1 + \bar{X}_i)(\bar{f}_2 + X_i) = \bar{f}_1 \bar{f}_2 + \bar{X}_i \bar{f}_2 + \bar{f}_1 X_i.$$

Hence, $F_2 = \bar{f}_1 + \bar{f}_2 + \bar{f}_1 \bar{f}_2 = \bar{f}_1 + \bar{f}_2(1 + \bar{f}_1) = \bar{f}_1 + \bar{f}_2$

Now, $F_1 \cdot F_2 = (f_1 + f_2)(\bar{f}_1 + \bar{f}_2) = f_1 \bar{f}_2 + \bar{f}_1 f_2 = f_1 \oplus f_2$.

But the complete test set for single fault on line i is given by,

$$T(i) = \left\{ t : \frac{df}{dX_i} = 1 \right\}, \text{ where } \frac{df}{dX_i} \text{ is the boolean difference of } f \text{ with respect to } X_i.$$

Now since $f = f(X_i) = f_1 X_i + f_2 \bar{X}_i$, hence we have,

$$\frac{df}{dX_i} = f(X_i = 1) \oplus f(X_i = 0) = f_1 \oplus f_2.$$

Hence the complete test set for single fault on line i is

$$T(i) = \{t : f_1 \oplus f_2 = 1\} = \{t : F_1 \cdot F_2 = 1\} = \{F_1\} \bigcap \{F_2\}.$$

Hence the theorem.

Theorem 2: If $f(x_1, x_2, \ldots, x_n)$ were a logical function realised by a combinational logic circuit, then the complete test set for all possible 2^p simultaneous multiple faults on any p lines $i_1, i_2, \ldots, i_p$ of the circuit is given by, $T = \{F_1\} \bigcap \{F_2\}$, where F_1 is the logical function obtained by taking the boolean sum of each product term of $f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})$ disregarding the Xs present in that term, and F_2, the logical function obtained by taking the boolean sum of each product term of $\overline{f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})}$ disregarding the Xs present in that term.

Proof: The theorem has already been proved for $p=1$. Let us now prove the theorem for $p=2$, *i.e.* for two lines i and j (say). Now, the most general form of the function $f(x_1, x_2, \ldots, x_n)$ when expressed in terms of X_i and X_j is given by,

$$f(X_i, X_j) = g_1 X_i + g_2 \bar{X}_i + g_3 X_j + g_4 \bar{X}_j + g_5 X_i X_j + g_6 \bar{X}_i X_j + g_7 X_i \bar{X}_j + g_8 \bar{X}_i \bar{X}_j + g_9 \tag{1}$$

where the gs are all functions of primary input variables $x_1, x_2, \ldots, x_n$ only.

The above expression can be written as

$$f(X_i, X_j) = f_1 X_i X_j + f_2 \bar{X}_i X_j + f_3 X_i \bar{X}_j + f_4 \bar{X}_i \bar{X}_j \tag{2}$$

where the fs are new functions of primary input variables $x_1, x_2, \ldots, x_n$ only; and $f_1+f_2+f_3+f_4 = g_1+g_2+g_3+g_4+g_5+g_6+g_7+g_8+g_9$.

Then $f_1+f_2+f_3+f_4$ = The logical function obtained from (1) by taking the boolean sum of each product term of $f(X_i, X_j)$ disregarding the Xs present in that term
$= F_1$ (say).

In a similar manner, we have,

$\bar{f}_1+\bar{f}_2+\bar{f}_3+\bar{f}_4$ = The logical function obtained from (1) by taking the boolean sum of each product term of $\overline{f(X_i, X_j)}$ disregarding the Xs present in that term
$= F_2$ (say)

Now, from relation (2) it can be readily seen that

$$f_1 = f(X_i=1, X_j=1) = f(1,1); \quad f_2 = f(X_i=0, X_j=1) = f(0,1);$$

$$f_3 = f(X_i=1, X_j=0) = f(1,0); \quad f_4 = f(X_i=0, X_j=0) = f(0,0).$$

From theorem 3 of Ku and Masson[3], we know that the complete test set for all possible simultaneous multiple faults on any two lines i and j is given by,

$$T = \left\{ t: \frac{df}{dX_i} + \frac{df}{dX_j} + \frac{d^2 f}{dX_i dX_j} = 1 \right\},$$

where df/dX_i and df/dX_j are the first-order boolean differences of f with respect to X_i and X_j respectively, and $d^2 f/dX_i dX_j$ is the second-order boolean difference of f with respect to X_i and X_j.

Now, $$\frac{df}{dX_i} + \frac{df}{dX_j} + \frac{d^2 f}{dX_i dX_j}$$

$$= [f(0, X_j) \oplus f(1, X_j)] + [f(X_i, 0) \oplus f(X_i, 1)] + [f(1,1) \oplus f(0,1) \oplus f(1,0) \oplus f(0,0)];$$

$$= X_j(f_2 \oplus f_1) + \bar{X}_j(f_4 \oplus f_3) + X_i(f_3 \oplus f_1) + \bar{X}_i(f_4 \oplus f_2) + (f_1 \oplus f_2 \oplus f_3 \oplus f_4).$$

(By Shannon's expansion theorem)

Now let $a = f_1 \oplus f_2$, $b = f_3 \oplus f_4$, $c = f_1 \oplus f_3$, $d = f_2 \oplus f_4$. (3)

Under this condition we must have,

$$a \oplus b = c \oplus d \text{ and also } a \oplus c = f_2 \oplus f_3 \text{ and } b \oplus c = f_1 \oplus f_4 \quad (4)$$

Thus we have,

$$\frac{df}{dX_i} + \frac{df}{dX_j} + \frac{d^2f}{dX_i dX_j} = X_j a + \bar{X}_j b + X_i c + \bar{X}_i d + (a \oplus b)(c \oplus d)$$

(Since from (3) and (4) we have, $f_1 \oplus f_2 \oplus f_3 \oplus f_4 = a \oplus b = c \oplus d = (a \oplus b)(c \oplus d)$)

$$= X_i X_j(a+b+c+d) + \bar{X}_i X_j(a+b+c+d) + X_i \bar{X}_j(a+b+c+d) + \bar{X}_i \bar{X}_j(a+b+c+d)$$

$$= a+b+c+d.$$

Again, $(f_1+f_2+f_3+f_4)(\bar{f}_1+\bar{f}_2+\bar{f}_3+\bar{f}_4)$

$$= (f_1 \oplus f_2) + (f_2 \oplus f_3) + (f_3 \oplus f_4) + (f_1 \oplus f_4) + (f_1 \oplus f_3) + (f_2 \oplus f_4)$$

$$= a + (a \oplus c) + b + (b \oplus c) + c + d \qquad \text{(Using (3) and (4))}$$

$$= a+b+c+d.$$

Hence we must have, $\frac{df}{dX_i} + \frac{df}{dX_j} + \frac{d^2f}{dX_i dX_j}$

$$= (f_1+f_2+f_3+f_4)(\bar{f}_1+\bar{f}_2+\bar{f}_3+\bar{f}_4) = F_1 \cdot F_2.$$

Thus the complete test set for all possible multiple faults on the two lines i and j is given by,

$$T = \{t : F_1 \cdot F_2 = 1\} = \{F_1\} \cap \{F_2\}.$$

Hence the theorem is true for $p = 2$.

The extension of the theorem for $p > 2$ is now obvious.

3. Algorithms for complete test set generation

Case 1: For single fault

Step 1: To find the complete test set for single fault on any line i of the combinational network, express the primary output of the network in terms of X_i in the sum of products form and denote it by $f(X_i)$ and hence find $\overline{f(X_i)}$ also in the sum of products form.

Step 2: From the expressions of $f(X_i)$ and $\overline{f(X_i)}$ obtained in step 1, compute the functions F_1 and F_2 by disregarding all the Xs present in the product terms and then taking the boolean sum of all the product terms of $f(X_i)$ and $\overline{f(X_i)}$, respectively.

Step 3: Obtain the required complete test set as $T(i) = \{F_1\} \bigcap \{F_2\}$.

Case 2: For all possible multiple faults

Step 1: To generate complete test set for all possible multiple faults on any p lines $i_1, i_2, \ldots, i_p$ of a combinational network, obtain the expression of $f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})$ in the sum of products form and hence find the expression of $\overline{f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})}$ also in the sum of products form.

Step 2: Disregarding the Xs present in all the product terms of $f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})$ and $\overline{f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})}$, obtain the boolean sum of all the terms of $f(X_{i_1}, X_{i_2}, \ldots, (X_{i_p})$ and $\overline{f(X_{i_1}, X_{i_2}, X_{i_3}, \ldots, X_{i_p})}$, respectively.

Step 3· Designate the two boolean sums obtained in step 2 as F_1 and F_2, respectively and obtain the required complete test set using the formula $T = \{F_1\} \bigcap \{F_2\}$.

4. Illustrative examples

Example 1: Let us first consider the network of fig. 1. We would like to generate the complete test set for the detection of S-a-0 single fault on the line i (as indicated in fig. 1) of this circuit. Then associating the logical variable X_i with the line i of the above circuit, we obtain,

$$f(X_i) = \overline{(\overline{X_i + x_1} + \overline{X_i + x_4} + \overline{\overline{x_1 + x_3} + x_2} + \overline{x_2 + x_4 + x_3})}$$

$$= \overline{(\bar{X}_i\bar{x}_1 + \bar{X}_i\bar{x}_4 + \overline{\bar{x}_1\bar{x}_3 + x_2} + \overline{\bar{x}_2\bar{x}_4 + x_3})}$$

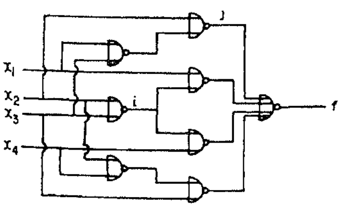

FIG. 1. Combinational network of Example 1.

$$= \overline{[\overline{\bar{X}_i\bar{x}_1} + \overline{\bar{X}_i\bar{x}_4} + \overline{(x_1+x_3)\bar{x}_2} + \overline{(x_2+x_4)\bar{x}_3}]}$$

$$= \overline{[\bar{X}_i\bar{x}_1 + \bar{X}_i\bar{x}_4 + x_1\bar{x}_2 + \bar{x}_2x_3 + x_2\bar{x}_3 + \bar{x}_3x_4]}$$

$$= (X_i+x_1)(X_i+x_4)(\bar{x}_1+x_2)(x_2+\bar{x}_3)(\bar{x}_2+x_3)(x_3+\bar{x}_4)$$

$$= (X_i+x_1x_4)(x_2+\bar{x}_1\bar{x}_3)(x_3+\bar{x}_2\bar{x}_4)$$

$$= (X_i+x_1x_4)(x_2x_3+\bar{x}_1\bar{x}_2\bar{x}_3\bar{x}_4)$$

$$= X_i(x_2x_3+\bar{x}_1\bar{x}_2\bar{x}_3\bar{x}_4)+x_1x_2x_3x_4.$$

Hence, $\overline{f(X_i)} = \overline{[f(X_i)]}$

$$= [\overline{X_i+x_1} + \overline{X_i+x_4} + \overline{x_1+x_3+x_2} + \overline{x_2+x_4+x_3}]$$

$$= \bar{X}_i\bar{x}_1 + \bar{X}_i\bar{x}_4 + x_1\bar{x}_2 + \bar{x}_2x_3 + x_2\bar{x}_3 + \bar{x}_3x_4.$$

(as calculated earlier)

Thus, we have, $F_1 = x_2x_3+\bar{x}_1\bar{x}_2\bar{x}_3\bar{x}_4+x_1x_2x_3x_4 = x_2x_3+\bar{x}_1\bar{x}_2\bar{x}_3\bar{x}_4$

and $F_2 = \bar{x}_1+\bar{x}_4+x_1\bar{x}_2+\bar{x}_2x_3+x_2\bar{x}_3+\bar{x}_3x_4 = \bar{x}_1+\bar{x}_2+\bar{x}_3+\bar{x}_4$

(Since $x+\bar{x}y = x+y$ and $x+xy=x$).

Thus, $F_1 = \{\phi 11\phi, 0000\}$ and $F_2 = \{0\phi\phi\phi, \phi 0\phi\phi, \phi\phi 0\phi, \phi\phi\phi 0\}$.

Hence, $T(i) = \{F_1\} \cap \{F_2\}$

$$= \{\phi 11\phi, 0000\} \cap \{0\phi\phi\phi, \phi 0\phi\phi, \phi\phi 0\phi, \phi\phi\phi 0\}$$

$$= \{0000, 011\phi, 1110\}.$$

The complete test set for line i stuck at 0 is then given by,

$$T(\text{Line } i \text{ -s-a-0}) = \{X_i\} \cap T(i)$$

$$= \{\bar{x}_2\bar{x}_3\} \cap T(i)$$

$$= \{\phi 00\phi\} \cap \{0000, 011\phi, 1110\}$$

$$= \{0000\}$$

$$= \{0\}.$$

Now let us obtain the complete test set for all possible 2^2 or four simultaneous multiple faults on lines i and j (as indicated in fig. 1) of the network of fig. 1. We have then,

$$f(X_i,X_j) = \overline{\overline{X_i+x_1} + X_j + \overline{X_i+x_4} + \overline{x_2+x_4} + x_3}$$

$$= \overline{\bar{X}_i\bar{x}_1 + X_j + \bar{X}_i\bar{x}_4 + \overline{\bar{x}_2\bar{x}_4 + x_3}}$$

$$= \overline{\bar{X}_i\bar{x}_1 + X_j + \bar{X}_i\bar{x}_4 + x_2\bar{x}_3 + \bar{x}_3x_4}$$

$$= (X_i+x_1)\bar{X}_j(X_i+x_4)(\bar{x}_2+x_3)(x_3+\bar{x}_4)$$

$$= \bar{X}_j(X_i+x_1x_4)(x_3+\bar{x}_2\bar{x}_4)$$

$$= \bar{X}_j(x_3X_i + x_1x_3x_4 + \bar{x}_2\bar{x}_4X_i)$$

$$= x_3X_i\bar{X}_j + x_1x_3x_4\bar{X}_j + \bar{x}_2\bar{x}_4X_i\bar{X}_j.$$

Hence, $F_1 = x_3 + x_1x_3x_4 + \bar{x}_2\bar{x}_4 = x_3 + \bar{x}_2\bar{x}_4.$

Again, $\overline{f(X_i, X_j)} = \bar{X}_i\bar{x}_1 + X_j + \bar{X}_i\bar{x}_4 + x_2\bar{x}_3 + \bar{x}_3x_4.$

Hence, $F_2 = \bar{x}_1 + 1 + \bar{x}_4 + x_2\bar{x}_3 + \bar{x}_3x_4 = 1.$

Thus, $\{F_1\} = \{\phi\phi1\phi, \phi0\phi0\}$ and $\{F_2\} = \{\phi\phi\phi\phi\}$.

Hence the complete test set for all possible 2^2 or four types of simultaneous multiple faults on the lines i and j of the network of fig. 1 is then given by,

$$\begin{aligned} T &= \{F_1\} \bigcap \{F_2\} \\ &= \{\phi\phi1\phi, \phi0\phi0\} \bigcap \{\phi\phi\phi\phi\} \\ &= \{\phi\phi1\phi, \phi0\phi0\} \\ &= \{0, 2, 3, 6, 7, 8, 10, 11, 14, 15\}. \end{aligned}$$

Example 2: Let us now discuss the application of the above theorems to generate complete test sets for the combinational logic circuit of fig. 2. Let us first apply theorem 1 to generate the complete test set for single fault on line 1 of the circuit of fig. 2. We have then, $f(X_1) = \bar{X}_1x_2\bar{x}_3 + \bar{X}_1\bar{x}_2x_3$ and hence $\overline{f(X_1)} = X_1 + \bar{x}_2\bar{x}_3 + x_2x_3$. Thus we have, $F_1 = x_2\bar{x}_3 + \bar{x}_2x_3$ and $F_2 = 1 + \bar{x}_2\bar{x}_3 + x_2x_3 = 1$. Hence, $\{F_1\} = \{\phi10, \phi01\}$ and $\{F_2\} = \{\phi\phi\bar{\phi}\}$. Thus the complete test set for single fault on line i is given by, $T(1) = \{F_1\} \bigcap \{F_2\} = \{\phi10, \phi01\} = \{1, 2, 5, 6\}$.

Now, let us obtain the complete test set for single fault on the internal line 13 of the circuit of fig. 2. Then we have, $f(X_{13}) = \bar{x}_1x_2X_{13} + \bar{x}_1x_3X_{13}$ and hence $\overline{f(X_{13})} = x_1 + \bar{x}_2\bar{x}_3 + \bar{X}_{13}$. Thus we have, $F_1 = \bar{x}_1x_2 + \bar{x}_1x_3$ and $F_2 = x_1 + \bar{x}_2\bar{x}_3 + 1 = 1$. Hence, $\{F_1\} = \{01\phi, 0\phi1\}$ and $\{F_2\} = \{\phi\phi\phi\}$. The complete test set for single fault on the internal line 13 is then given by,

$$T(13) = \{F_1\} \bigcap \{F_2\} = \{01\phi, 0\phi1\} = \{1, 2, 3\}.$$

In a similar manner the complete test sets for single fault on the remaining lines of the circuit of fig. 2 can be generated.

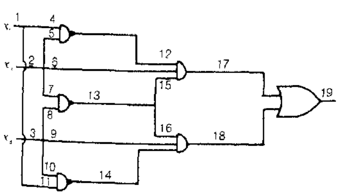

FIG. 2. Combinational network of Example 2.

Finally, let us discuss the application of theorem 2 for generating the complete test set for all possible 2^3 or eight simultaneous multiple faults on lines 4, 13 and 14 of the combinational network shown in fig. 2. In this case, we have, $f(X_4, X_{13}, X_{14}) = x_2\bar{X}_4X_{13} + x_3X_{13}X_{14}$ and $\overline{f(X_4, X_{13}, X_{14})} = \bar{x}_2\bar{x}_3 + \bar{x}_2\bar{X}_{14} + \bar{x}_3X_4 + X_4\bar{X}_{14} + \bar{X}_{13}$. Hence, $F_1 = x_2 + x_3$ and $F_2 = \bar{x}_2\bar{x}_3 + \bar{x}_2 + \bar{x}_3 + 1 + 1 = 1$, so that $\{F_1\} = \{\phi 1 \phi, \phi\phi 1\}$ and $\{F_2\} = \{\phi\phi\phi\}$. Thus the complete test set for all possible 2^3 or eight multiple faults on lines 4, 13 and 14 of the circuit of fig. 2 is given by,

$$T = \{F_1\} \bigcap \{F_2\} = \{\phi 1 \phi, \phi\phi 1\} = \{1, 2, 3, 5, 6, 7\}.$$

5. Conclusion

In this contribution, a new technique is described for the detection of single and multiple faults in a combinational network. For MSI chips, the present scheme is superior to the boolean difference methods because of the following: (i) The key issue in the present scheme is to find the expressions of $f(X_i)$ and $\overline{f(X_i)}$ or to find the expressions of $f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})$ and $\overline{f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})}$ in the sum of products form. Thus the tedious steps of algebraic manipulation involved in the evaluation of first and higher-order boolean differences and hence to arrive at the complete test sets in the boolean difference methods[1-9] can be dispensed with. (ii) Since the complete test sets are finally obtained by finding the intersection of the sets $\{F_1\}$ and $\{F_2\}$, the diagnosis algorithms in the present scheme will be more easy to apply compared to the boolean difference techniques.

In spite of the above advantages of the present scheme, such a line-by-line testing of the network will be troublesome particularly for LSI chips because of the extra cost that will be called for in diagnosing faults in the circuit. In such a case one would prefer using a simplified test set merely to detect the presence of such faults and if a fault exists, the question of replacing the entire circuit rather than repairing it must be considered.

Notations

1. X_i : Let $f(x_1, x_2, \ldots, x_n)$ be a logical function realised by a combinational network. Then the logical variable associated with any line i of the network will be denoted by X_i.

2. $f(X_i)$: Let $f(x_1, x_2, \ldots, x_n)$ be a logical function realised by a combinational network. The primary output of the network can be expressed in terms of X_i and denoted by $f(X_i)$.

3. $f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})$: Let $f(x_1, x_2, \ldots, x_n)$ be a logical function realising a combinational network. The primary output of the network can be expressed in terms of the logical variables $X_{i_1}, X_{i_2}, \ldots, X_{i_p}$ associated with p lines $i_1, i_2, \ldots, i_p$ of the network and denoted by $f(X_{i_1}, X_{i_2}, \ldots, X_{i_p})$.

4. $\{f\}$ Let $f(x_1, x_2, \ldots, x_n)$ be a logical function realising a combinational network. Then the set of minterms of the function $f(x_1, x_2, \ldots, x_n)$ will be denoted by $\{f\}$.

References

1. SELLERS, F. F. JR., HSIAO, M. Y AND BEARNSON, L. W. — Analyzing errors with Boolean difference, *IEEE Trans.*, 1968, **C-17**, 676-683
2. YAU, S. S. AND TANG, Y. S. — An efficient algorithm for generating complete test sets for combinational logic circuits, *IEEE Trans.*, 1971, **C-20**, 1245-1251.
3. KU, C. T. AND MASSON, G. M. — The boolean difference and multiple fault analysis, *IEEE Trans*, 1975, **C-24**, 62 71.
4. MARINOS, P. N. — *Boolean differences as a means for deriving complete sets of input test sequences for fault diagnosis in switching systems*, Bell Telephone Laboratories, Greensboro, N.C., Tech. Memo MM-69-6313-1, August 1969.
5. MARINOS, P. N. — A method of deriving minimal complete sets of test-input sequences using boolean differences, *Proc. Int. Computer Group Conv.*, pp. 240-246, Washington, D.C., June 1970.
6. REED, I. S. — Boolean difference calculus and fault finding, *SIAM J. Appl. Math.*, 1973, **24**, 134 142.
7. CHIANG, A C. L. REED I. S. AND BANES, A. V. — Path sensitization, partial Boolean differences and automated fault diagnosis, *IEEE Trans.*, 1972, **C-21**, 189 195.
8. MARINOS, P. N. — Derivation of minimal complete sets of test-input sequences using boolean differences, *IEEE Trans.*, 1971, **C-20**, 25-32.
9. MARINOS, P. N. — Partial boolean differences and their application to fault detection, *Fourth Asilomar Conf. Circuits Systems*, Pacific Grove, Cal., Nov. 1970.
10. BHOWMIK, K. B. THAKUR R. K. AND BHATTACHARJEE, P. R. — The boolean difference and multiple fault test set in combinational network, *Calcutta ICCCS*, Jadavpur University, India, pp. 28 (Abstract), December 1981.
11. BANERJEE, S. N. THAKUR R. K AND BHATTACHARJEE, P. R. — An efficient algorithm for single and multiple fault test sets generation, *Int. J. Computer Math.*, 1985, **18**, 121 133.
12. BASU, S. K. PAUL, J. C. AND BHATTACHARJEE P. R. — Complete test set generation for bridging faults in combinational logic circuits, *Inf. Sci.*, 1986, **38**, 257 269.