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NECESSARY AND SUFFICIENT CONDITIONS FOR REALIZABILITY OF GIVEN SWITCHING FUNCTIONS

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REALIZABILITY OF GIVEN SWITCHING FUNCTIONS

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University of Illinois, 1966

ABSTRACT

In this paper the author established a relationship among switching functions between any two points of a contact network and proved that the relationship is in fact necessary and sufficient for switching functions to be assigned to an actual contact network, that is, realizable.

In addition he picked up one particular type of switching function, that is, single-contact switching functions and established a necessary condition for switching functions to be single-contact.

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I. INTRODUCTION

Among switching functions between any two points of a contact network there must be some relationship. They cannot be arbitrary, so the author started with a general question of what are conditions for switching functions to be realized as a contact network.

In the first two theorems there are mentioned relationships for switching functions between any two of three points in a contact network to satisfy. In fact Theorem II states that the relation is necessary and sufficient for given switching functions to be realizable.

In the next two they are expanded to relationships among arbitrarily many points, and also Theorem IV states that the relation is necessary and sufficient for given switching functions to be realizable.

These relationships should be satisfied by any kind of contact networks. Other conditions imposed on switching functions either imply or do not conflict with them. As an example of the former the author picked up one particular type of switching functions that is single-contact switching functions and established a necessary condition for switching functions to be single-contact. As is mentioned later this condition seems to the author to be also sufficient. But he has not proved it yet. This would be a good future problem.

II. RELATIONSHIPS AMONG SWITCHING FUNCTIONS IN A CONTACT NETWORK

Definition I

A contact network is a non-oriented graph with a Boolean variable x_i associated with each edge [1].

Definition II

A path product ij is the product of the variables associated with the edges of a path from vertex i to vertex j of the contact network [1].

Definition III

Any switching function F can be written as a Boolean sum of Boolean products of Boolean variables. That is

$$F = \Sigma\, x_1^{i_1} \cdot x_2^{i_2} \text{-------} \cdot x_n^{i_n}$$

where x_k are Boolean variables, $i_j = 1$, or 0, j, k = 1, ---, n, and Σ is a Boolean sum. We call this form the standard form of the switching function F. "." is often omitted within the standard form.

In the following discussion it is assumed (without loss of generality) that switching functions are in the standard form.

We can add redundant terms to the standard form of a switching function so that its terms correspond one-to-one to paths of the contact network to which the switching function is assigned.

Theorem I

Given switching functions F_{ab} and F_{bc} between any two of three vertices a, b, and c in the contact network, the third switching function, that is F_{ac} must satisfy the following equation:

$$F_{ac} + F_{ab} \cdot F_{bc} = F_{ac}$$

where "$\cdot$" is Boolean multiplication and "+" is Boolean addition.

Proof

Each term of F_{ac} (notice that F is in the standard form) corresponds to a path between a and c. But not every path between a and c corresponds to a term of F_{ac}. It is known that path product of those paths which do not correspond to any term of F_{ac} is a redundant term of F_{ac}.

Let F'_{ac} be the switching function to whose terms correspond paths between a and c one-to-one.

Then $F_{ac} = F'_{ac}$; hence, $F_{ac} + F'_{ac} = F_{ac}$.

Similarly define F'_{ab} and F'_{bc}.

Then since $F_{ab} = F'_{ab}$ and $F_{bc} = F'_{bc}$; hence, $F'_{ab} \cdot F'_{bc} = F_{ab} \cdot F_{bc}$.

Every term of $F'_{ab} \cdot F'_{bc}$ is the Boolean product of a path product ab and a path product bc.

When two path products, one in F'_{ab} and the other in F'_{bc}, are multiplied the edges in paths corresponding to the two path products form a path ac, as shown in Fig. 1(a). In addition they may form circuits which are connected to the path ac, a path between b and a vertex in the path ac, or combination of these two, as shown in Fig. 1(b), (c), and (d), respectively.

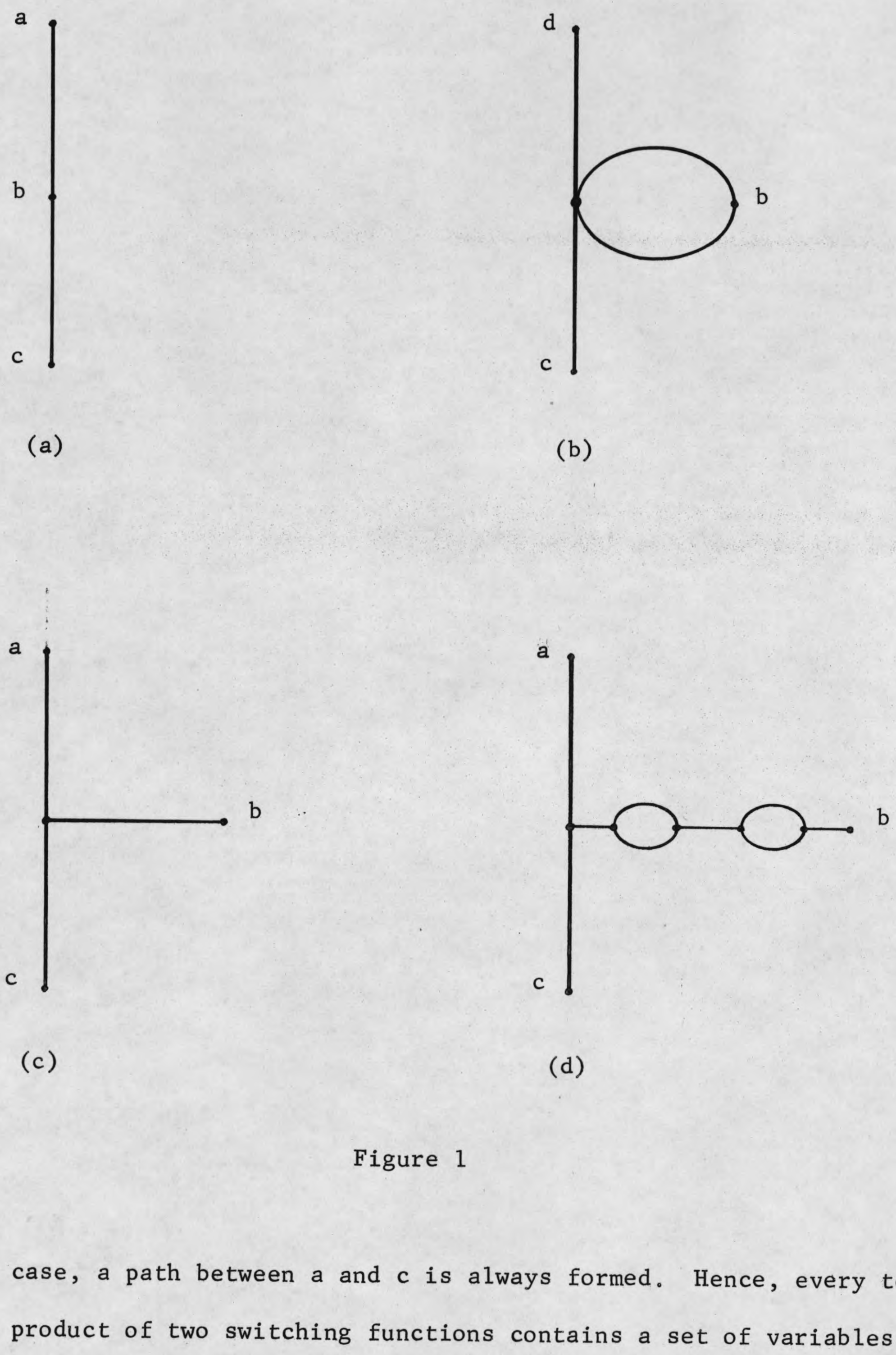

Figure 1

In any case, a path between a and c is always formed. Hence, every term of the product of two switching functions contains a set of variables which appear in a certain term of F'_{ac} and it may contain other variables, too. Hence, every term of the product is either equal to a term of F'_{ac} or to the product of a term of F'_{ac} and other variables.

Hence, $F'_{ac} + F'_{ab} \cdot F'_{bc} = F'_{ac}$.

Hence, $F_{ac} + F'_{ac} + F'_{ab} \cdot F'_{bc} = F_{ac} + F'_{ac} = F_{ac}$.

But, $F'_{ab} \cdot F'_{bc} = F_{ab} \cdot F_{bc}$.

Hence, $F_{ac} = F_{ac} + F'_{ac} + F'_{ab} \cdot F'_{bc}$

$= F_{ac} + F'_{ac} + F_{ab} \cdot F_{bc}$

$= F_{ac} + F_{ab} \cdot F_{bc}$.

Example

Let the contact network be given as in Fig. 2.

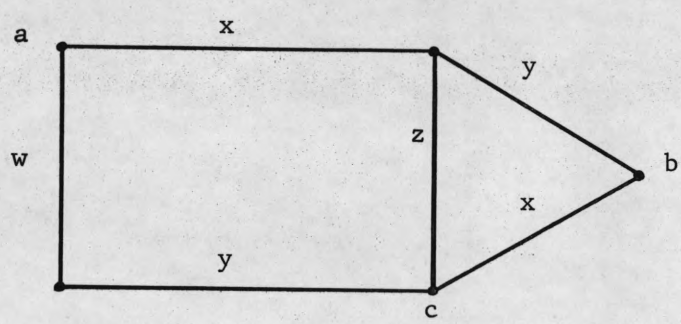

Figure 2

Then $F_{ab} = xy + xz + wyz$

$F_{bc} = x + yz$

$F_{ac} = wy + xz + xy$

$F_{ab} \cdot F_{bc} = xy + xz + wyz$.

Hence $F_{ac} + F_{ab} \cdot F_{bc} = xy + xz + wy = F_{ac}$.

Theorem II

For given three switching functions F_{ab}, F_{bc}, and F_{ca}, there exists a contact network containing vertices a, b, and c, such that switching functions between a, b, and c are F_{ab}, F_{bc}, and F_{ca} if, and only if, the following relations hold:

$$F_{ab} + F_{bc} \cdot F_{ca} = F_{ab}$$

$$F_{bc} + F_{ca} \cdot F_{ab} = F_{bc}$$

$$F_{ca} + F_{ab} \cdot F_{bc} = F_{ca}$$

<u>Proof</u> "if" part

The contact network shown in Fig. 3 is a desired contact network.

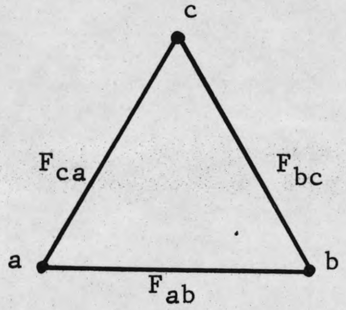

Figure 3

"only if" part

By letting F_{ab} the third switching function in Theorem I we obtain $F_{ab} + F_{bc} \cdot F_{ca} = F_{ab}$. Similarly the other two can be obtained.

<u>Example</u>

Let the contact network be given as in Fig. 4.

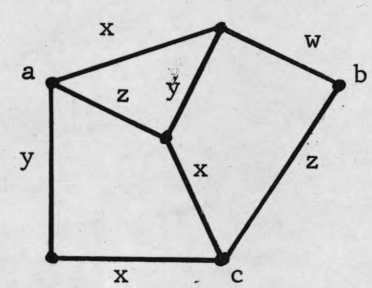

Figure 4

Then $F_{ab} = wx + xz + wyz$

$F_{bc} = z + wxy$

$F_{ac} = xy + xz + wyz$

$F_{ab} \cdot F_{bc} = xz + wyz + wxy$

$F_{bc} \cdot F_{ac} = xz + wxy + wyz$

$F_{ac} \cdot F_{ab} = xz + wxy + wyz$

Hence $F_{ab} + F_{bc} \cdot F_{ac} = wx + xz + wyz = F_{ab}$

$F_{bc} + F_{ac} \cdot F_{ab} = z + wxy = F_{bc}$

$F_{ac} + F_{ab} \cdot F_{bc} = xy + xz + wyz = F_{ac}$

Theorem III

Let F_{ab} be a switching function between a and b. Also let F_{bc}, F_{cd}, -----, F_{ma} be switching functions between any two vertices in a path between a and b. Then $F_{ab} + F_{bc} \cdot F_{cd} \cdot ----- \cdot F_{ma} = F_{ab}$.

Proof

By induction on the number n of vertices in a path between a and b except a and b.

By Theorem I it is true for n = 1.

Assume that it is true for n = k.

Then $F_{ab} + F_{bc} \cdot F_{cd} \cdot ----- \cdot F_{ka} = F_{ab}$.

k + 1

$$F_{ab}+F_{bc}\cdot F_{cd}\cdot ----- \cdot F_{k\,k+1}\cdot F_{k+1a}=F_{ab}+F_{bc}\cdot F_{cd}\cdot ----- \cdot F_{k+k}\cdot F_{ka}+F_{bc}\cdot F_{cd}\cdot ----- \cdot F_{k\,k+1}\cdot F_{k+1a}$$

$$=F_{ab}+(F_{bc}\cdot F_{cd}\cdot ----- \cdot F_{k+k})\cdot(F_{ka}+F_{k\,k+1}\cdot F_{k+1a})$$

$$=F_{ab}+F_{bc}\cdot F_{cd}\cdot ----- \cdot F_{k+k}\cdot F_{ka}$$

$$=F_{ab}\,.$$

Example

Let the contact network be given as in Fig. 5.

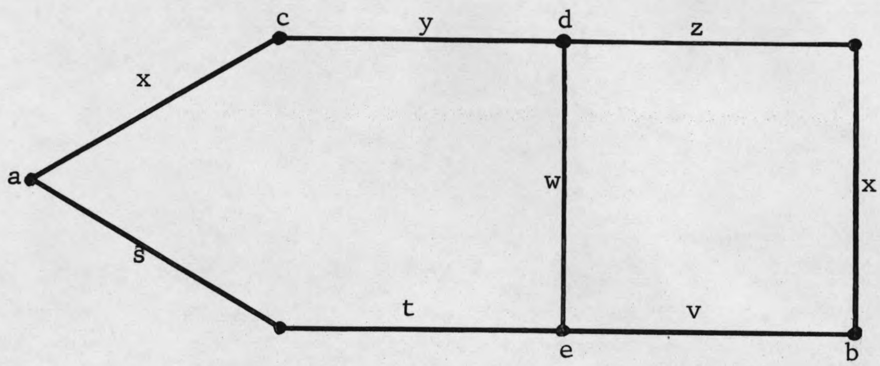

Figure 5

Then $F_{ab} = vwxy + xyz + stv + stwxz$

$F_{bc} = x + stwy$

$F_{cd} = y + stwx + stvxz$

$F_{de} = w + vxz + stxy$

$F_{eb} = v + wxz + stxyz$

$F_{ac} \cdot F_{cd} = xy + stwy + stwx + stvxz$

$F_{ac} \cdot F_{cd} \cdot F_{de} = wxy + vxyz + stxy + stwy + stwx + stvxz$

$F_{ac} \cdot F_{cd} \cdot F_{de} \cdot F_{eb} = vwxy + stwxz$

Hence $F_{ab} + F_{ac} \cdot F_{cd} \cdot F_{de} \cdot F_{eb} = vwxy + xyz + stv + stwxz = F_{ab}$

Definition IV

Switching functions are realizable if there exists a contact network to which they can be assigned.

Definition V

Let $\{F_{ab}\}$ be a set of given switching functions. Then a corresponding network N of $\{F_{ab}\}$ is a contact network formed by connecting an edge between vertex a and vertex b whose weight is F_{ab} for all F_{ab} in $\{F_{ab}\}$.

Example

Given F_{ab}, F_{bc}, F_{ca}, F_{cd}, and F_{bd} its corresponding network is as in Fig. 6.

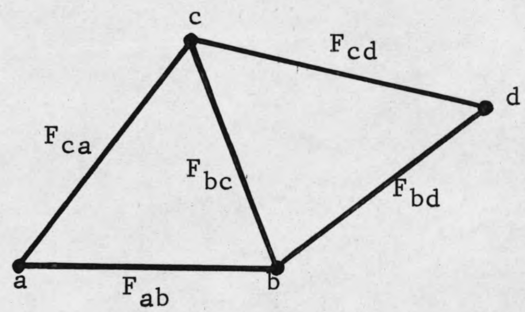

Figure 6

Theorem IV

Switching functions are realizable if, and only if, for all possible paths between any two adjacent vertices in the corresponding graph the following relation holds;

$$F_{ab} + F'_{ab} = F_{ab}$$

where F_{ab} = given switching function between vertex a and b

F'_{ab} = Boolean sum of all possible path products between vertex a and vertex b less F_{ab}.

Proof "if" part

A corresponding network is a desired network. This is clear by definition of a corresponding network.

"only if" part

By induction on the number of paths. Let a and b be arbitrary adjacent points in the contact network. Let P_1, P_2, ---, P_n, be all possible paths between a and b. Let F_1, F_2, ---, F_n, be path products corresponding to P_1, P_2, ---, P_n, respectively.

n = 1. By Theorem III, $F_{ab} + F_1 = F_{ab}$. Assume that it is true for n = k.

Then
$$F_{ab} + F_1 + F_2 + \text{---} + F_k + F_{k+1} = (F_{ab} + F_1 + \text{---} + F_k) + F_{k+1}$$
$$= F_{ab} + F_{k+1}$$
$$= F_{ab} .$$

Example

Let the contact network be given as in Fig. 7

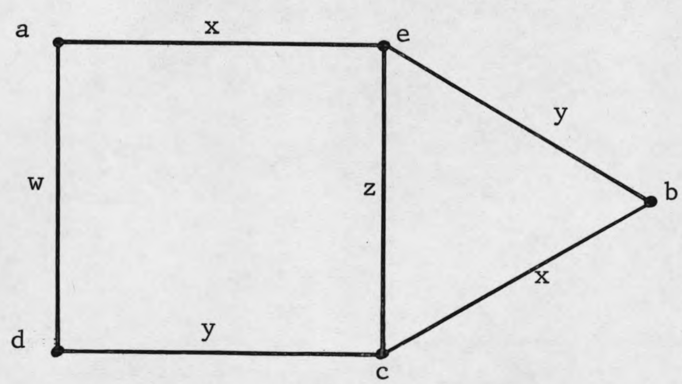

Figure 7

Then $F_{bc} = x + yz$

$F_{ae} = x + wyz$

$F_{eb} = y + xz$

$F_{ce} = z + xy$

$F_{ad} = w + xy$

$F_{dc} = y + wxz$

$F'_{bc} = F_{be} \cdot F_{ec} + F_{be} \cdot F_{ea} \cdot F_{ad} \cdot F_{dc} = xy + yz + xz$

Hence $F_{bc} + F'_{bc} = x + yz = F_{bc}$

$F'_{ae} = F_{ad} \cdot F_{dc} \cdot F_{ce} + F_{ad} \cdot F_{dc} \cdot F_{cb} \cdot F_{be} = xy + wxz + wyz$

Hence $F_{ae} + F'_{ae} = x + wyz = F_{ae}$

$F'_{eb} = F_{ec} \cdot F_{cb} + F_{ea} \cdot F_{ad} \cdot F_{dc} \cdot F_{cb} = xy + xz + yz$

Hence $F_{eb} + F'_{eb} = y + zx = F_{eb}$

$F'_{ce} = F_{cb} \cdot F_{be} + F_{ea} \cdot F_{ad} \cdot F_{dc} = xy + yz + zx$

Hence $F_{ce} + F'_{ce} = z + xy = F_{ce}$

$F'_{ad} = F_{dc} \cdot F_{ce} \cdot F_{ea} + F_{dc} \cdot F_{cb} \cdot F_{be} \cdot F_{ea} = xy + wxz + wyz$

Hence $F_{ad} + F'_{ad} = w + xy = F_{ad}$

$F'_{dc} = F_{ce} \cdot F_{ea} \cdot F_{ad} + F_{bc} \cdot F_{eb} \cdot F_{ea} \cdot F_{ad} = xy + wxz + wyz$

Hence $F_{dc} + F'_{dc} = y + wxz = F_{dc}$.

III. ON SINGLE-CONTACT NETWORKS

Definition VI

Ring product $\otimes$ is defined as follows:

$$x_i \otimes x_j = x_i \cdot x_j \qquad \text{if } x_i \neq x_j$$

$$x_i \otimes x_j = 1 \qquad \text{if } x_i = x_j$$

where "." is Boolean multiplication.

Definition VII

Single-contact network is a contact network in which each edge has a different Boolean variable associated with it. The switching function of such a network (between any two terminals) is a single-contact function [1][2].

Theorem V

If given switching functions are single-contact functions then for any three vertices a, b, and c in the contact network the following equation holds:

$$F_{ab} \otimes F_{bc} = F_{ac} .$$

Proof

Since by the proof Theorem I $F'_{ab} \otimes F'_{bc} = F_{ab} \otimes F_{bc}$, we can prove this by showing $F'_{ab} \otimes F'_{bc} = F_{ac}$. As in the proof of Theorem I, when two path products, one in F'_{ab} and the other in F'_{bc}, are multiplied the edges in paths corresponding to the two path products form a path ac. In addition they may also form circuits which are connected to the path ac, a path between b and a vertex in a path ac or combination of these two as in the proof of Theorem I.

Case 1) All edges form a path ac.

The product of two path products is equal to a certain term of F'_{ac} .

Case 2) Edges form a path between b and a vertex, say d, in a path ac in addition to the path ac.

Edges in the path bd are both in a path ab and a path bc and variables associated with these edges take the form of the square in the product $F_{ab} \cdot F_{bc}$. So by letting squares to be 1 we eliminate variables of the edges which form a path bd.

Case 3) Edges form circuits which are connected to a path ac in addition to the path ac.

There are always at least two paths between b and a vertex, say d, in the path ac. Hence, for every product P_1 of two path products of this case there exists a ring product P_2 of two path products of the type of Case 2) such that $P_1 + P_2 = P_2$.

Case 4) Combination of Case 2) and Case 3).

Similar to Case 3).

Since all paths between a and c are obtained by combining all paths between b and c with all paths between a and b, hence, $F'_{ab} \otimes F'_{bc} = F_{ac}$. Hence, $F_{ab} \otimes F_{bc} = F_{ac}$.

Example

Let the contact network be given as in Fig. 8.

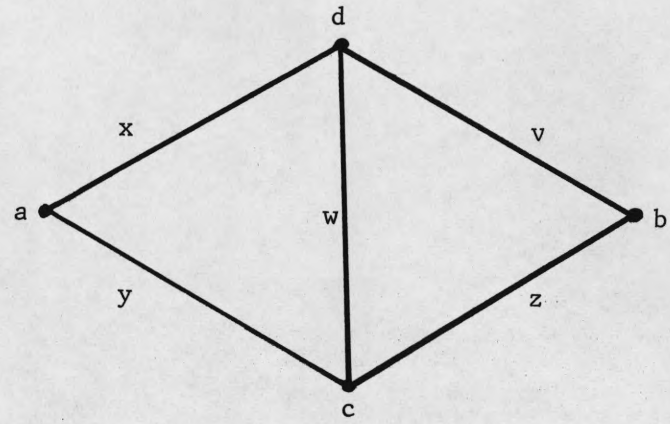

Figure 8

Then $F_{ab} = xv + wxz + vwy + yz$

$F_{ad} = x + wy + vyz$

$F_{ac} = y + wx + vxz$

$F_{bc} = z + vw + vxy$

$F_{bd} = v + wz + xyz$

$F_{cd} = w + xy + vz$

Hence $F_{ab} \otimes F_{bc} = y + wx + vxz = F_{ac}$

$F_{ac} \otimes F_{bc} = vx + yz + wxz + vwy = F_{ab}$

$F_{ab} \otimes F_{ac} = z + vw + vxy = F_{bc}$

$F_{ab} \otimes F_{bd} = x + wy + vyz = F_{ad}$

$F_{ab} \otimes F_{ad} = v + wz + xyz = F_{bd}$

$F_{ad} \otimes F_{bd} = vx + yz + vwy + wxz = F_{ab}$

$F_{ac} \otimes F_{ad} = w + xy + vz = F_{cd}$

$F_{ac} \otimes F_{cd} = x + wy + vyz = F_{ad}$

$F_{ad} \otimes F_{cd} = y + wx + vxz = F_{ac}$

$F_{bc} \otimes F_{cd} = v + wz + xyz = F_{bd}$

$F_{bc} \otimes F_{bd} = vz + w + xy = F_{cd}$

$F_{cd} \otimes F_{bd} = vw + z + vxy = F_{bc}$.

IV. FURTHER PROBLEMS

For any contact networks conditions of Theorem II or IV should be satisfied if they actually exist. Hence, other conditions such as single-contact realization or minimum realization should either include those conditions or be put together with them. The condition of Theorem V is one of the former type conditions. As is mentioned in introduction it looks sufficient for given switching functions to be realized as a single-contact network. Considering the reasoning of the proof of Theorem V, this does not look an unreasonable proposition.

There is no way of finding switching function between arbitrary two vertices in a contact network, where some of them are known, even with Theorems II, III, and IV because switching functions do not form a group with operations Boolean addition or multiplication. That is, there are many switching functions which satisfy conditions of Theorems II, III, and IV. It will be useful to find such operation that forms a group together with such switching functions.

Although the above two are the application of the result obtained at present, the author believes that there are much more applications since the theorems are so simple and general.

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In this paper the author established a relationship among switching functions between any two points of a contact network and proved that the relationship is in fact necessary and sufficient for switching functions to be assigned to an actual contact network, that is, realizable.

In addition he picked up one particular type of switching function, that is, single-contact switching functions and established a necessary condition for switching functions to be single-contact.

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