Fault Diagnosis in Distribution Substations Using CE-Nets via Boolean Rule Matrix Transformations

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Abstract: A new method for estimating fault sections in power substations is proposed. In this paper, the knowledge representation and inference procedures based on the cause-effect networks (CE-Nets) and Boolean rule matrix transformation techniques are presented. A CE-Net is a graphic modeling tool for representing the causality between faults and actions of protective devices. By transforming the established CE-Nets into matrix forms, the possible fault sections can be estimated through simple matrix operations. The method is superior to existing production systems in the inference speed and the process of implementation. Since the proposed reasoning methods require only simple matrix operations in a parallel manner, it is well suitable for on-line applications. The proposed method has been tested on a typical Taiwan Power Company's (Taipower) secondary substation. From the experimental results, it is found that the proposed method can estimate fault sections very efficiently.

Keywords: Fault diagnosis, Cause-effect network, Boolean rule matrix

I. INTRODUCTION

When a fault occurs in distribution systems, it is imperative to limit the impact of outages to the minimum and to take proper actions to restore the faulted area as soon as possible. This requires that the faulted sections first be identified from the information of operated protective devices, which is the main issue of fault diagnosis in distribution systems. In automated substations, a fault may cause large number of alarm messages in a short period of time and pour them into operator's consoles. It will impose a heavy stress on the operator and influence the operator to make a correct decision. Moreover, multiple faults may take place and protective devices may fail. In such situations, it becomes more complicated and difficult to pick up the cause of the fault under emergency. Therefore, it is important to develop some tools of providing rapid and correct fault analysis to assist operators in the aforementioned situations.

In the past decades, various fault diagnosis techniques have been proposed in the literature [1-7], such as Expert Systems (ES) and Artificial Neural Networks (ANN). Although the ES based approach offers powerful solutions, it still suffers from some imperfections such as slow response time and difficulty in database maintenance. On the other hand, the ANN method still remains some problems unsolved in practical application so far, such as slow convergence in the training process, and determination of the network parameters like hidden units, layers, learning rate and momentum value. In addition, when any configuration of the system changes, the related ANN needs to be re-trained.

In this paper, the CE-Nets knowledge representation and matrix-based inference procedures are proposed to provide a better way for estimating fault sections in automated distribution substations.

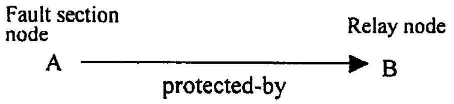
II. CAUSE-EFFECT NETWORK

Cause-effect network represents causality between faults and actions of protective relays and circuit breakers, including the three kinds of nodes below [8],

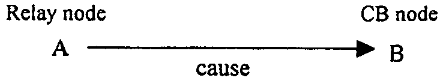
- *Fault section node*
  This node represents a section hit by a fault.
- *Relay node*
  This node indicates the action of a protective relay.
- *CB node*
  This node means the action of a circuit breaker.

In addition, there are three kinds of arcs

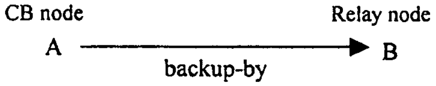
- Protected-by
  Means that the fault of section A causes the action of relay B.



- Cause
  Means that the action of relay A causes the trip of circuit breaker B.



- Backup-by
  Means that the failure of circuit breaker A causes the action of relay B.



A simple model distribution system, as shown in Fig.1, is used to illustrate the knowledge representation by the CE-Nets. The model system is protected by Over Current (CO) relays, Low-energy Over Current (LCO) relays and

Circuit Breakers (CB). Suppose that a fault occurs at F1, it causes the action of relay CO1, which trips the circuit breaker CB1. As CB1 fail to open at this time, the backup protective relay CO3 will actuate to trip circuit breaker CB3. This event is shown by the portion of dashed line in Fig. 2.

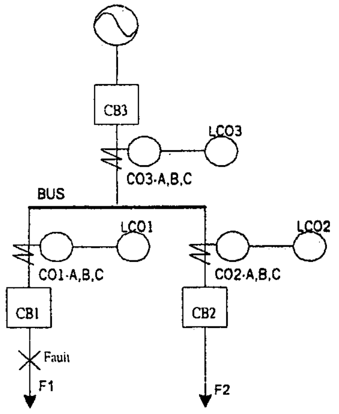


Fig. 1: A simple model distribution system

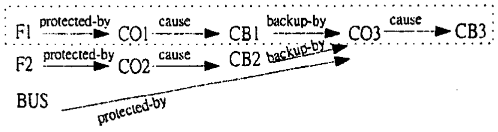


Fig.2: CE-Nets of model system

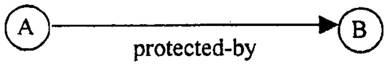
III. MATRIX REPRESENTATION OF CE-NETS

Corresponding to a given CE-Net model, the rule matrix is defined as follows:

A rule matrix contains all ones on the diagonal and with Boolean entries (0 or 1) via the three following cases

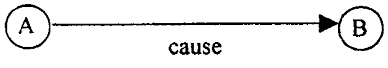
1. Protected-by

Cj="fault section" Ci="action of relay"



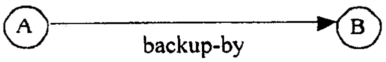
2. Cause

Cj="action of relay" Ci="CB trip"



3. Backup-by

Cj="CB failure" Ci="action of backup relay"



Ci, Cj are conditions from nodes of given CE-Nets. The truth of condition Cj implies the truth of condition Ci, in matrix representation, R(i,j)=1, where R is the rule matrix of the associated CE-Nets, otherwise R(i,j)=0. Here, we define the following column vectors for matrix operations in later sections.

❒ Truth state vector (T)

$$T(i)=\begin{cases}1, & \text{if } Ci \text{ is true}\\ 0, & \text{otherwise}\end{cases}$$

❒ Fault node vector (F)

$$F(i)=\begin{cases}1, & \text{if } Ci \in \text{fault section node}\\ 0, & \text{otherwise}\end{cases}$$

❒ Backup condition vector (B)

$$B(i)=\begin{cases}1, & \text{if } Ci \in \text{CB node of backup -by}\\ 0, & \text{otherwise}\end{cases}$$

❒ Transformation Vector (TV)

$\mathrm{TV} \equiv \mathrm{R}^{\mathrm{T}} \oplus \mathrm{T}$

where "$\oplus$" is the multiplication of two matrices, which replace real multiplication and addition with AND and OR respectively.

For example,

$$\begin{bmatrix}1 & 1\\ 0 & 1\end{bmatrix} \oplus \begin{bmatrix}0\\ 1\end{bmatrix} = \begin{bmatrix}(1\ AND\ 0)\ OR\ (1\ AND\ 1)\\ (0\ AND\ 0)\ OR\ (1\ AND\ 1)\end{bmatrix} = \begin{bmatrix}1\\ 1\end{bmatrix}$$

❒ Fault Section Vector (FSV)

$\mathrm{FSV} \equiv (\mathrm{TV}-\mathrm{T}) \odot \mathrm{F}$

where "$\odot$" is the AND operation of two matrices.

For example,

$$\begin{bmatrix}0\\ 0\\ 1\end{bmatrix} \odot \begin{bmatrix}1\\ 0\\ 1\end{bmatrix} = \begin{bmatrix}0 \text{ AND } 1\\ 0 \text{ AND } 0\\ 1 \text{ AND } 1\end{bmatrix} = \begin{bmatrix}0\\ 0\\ 1\end{bmatrix}$$

❒ Elimination vector (E)

$\mathrm{E} \equiv \mathrm{T} \odot \mathrm{B}$

To explain matrix representation of the CE-Nets, Fig. 3 is used for illustration.

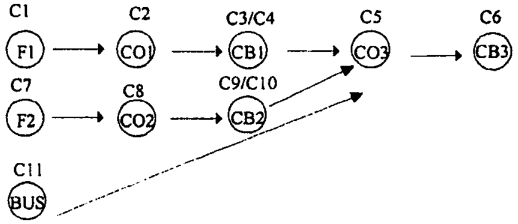


Fig. 3: CE-Nets for matrix representation

By observing the connection of each nodes, the rule matrix of Fig. 3 can therefore be constructed as

$$\mathbf{R}=\begin{array}{c}\begin{array}{ccccccccccc} C1 & C2 & C3 & C4 & C5 & C6 & C7 & C8 & C9 & C10 & C11 \end{array} \\ \left[\begin{array}{ccccccccccc}
1&0&0&0&0&0&0&0&0&0&0\\
1&1&0&0&0&0&0&0&0&0&0\\
0&1&1&0&0&0&0&0&0&0&0\\
0&0&0&1&0&0&0&0&0&0&0\\
0&0&0&1&1&0&0&0&0&1&1\\
0&0&0&0&1&1&0&0&0&0&0\\
0&0&0&0&0&0&1&0&0&0&0\\
0&0&0&0&0&0&1&1&0&0&0\\
0&0&0&0&0&0&0&1&1&0&0\\
0&0&0&0&0&0&0&0&0&1&0\\
0&0&0&0&0&0&0&0&0&0&1
\end{array}\right]\end{array}\begin{array}{c} \\ C1\\C2\\C3\\C4\\C5\\C6\\C7\\C8\\C9\\C10\\C11\end{array}$$

C1: Fault occurs at F1 section
C2: Relay CO1 actuated
C3: Circuit Breaker CB1 tripped
C4: CO1 actuated, but CB1 failed (i.e., $C2 \wedge \overline{C3}$)
C5: Relay CO3 actuated
C6: Circuit Breaker CB3 tripped
C7: Fault occurs at F2 section
C8: Relay CO2 actuated
C9: Circuit Breaker CB2 tripped
C10: CO2 actuated, but CB2 failed (i.e., $C8 \wedge \overline{C9}$)
C11: Fault occurs at BUS section

IV. INFERENCE PROCEDURES

The proposed inference procedures are achieved through truth state transformations based on Boolean value operations, which preserve truth state and propagate truths as implied by the implication digraphs [9].

Steps of inference:

Step1. Establishing Boolean rule matrix, R, of given CE-Nets.
Step2. Deriving truth state vector, T, from fault information.
Step3. Calculating Transformation Vector, TV.
Step4. Calculating Fault Section Vector, FSV.
Step5. Selecting fault candidates from FSV which entries comprise "1".
Step6. Calculating Elimination vector, E. If E is a zero vector, the fault candidates selected from step 5 are chosen as the fault section. On the other hand, if E is not a zero vector, the main protective section of backup relays that corresponding to nonzero entries of E is eliminated from fault candidates.

V. EXAMPLES

We use a realistic Taipower's secondary substation to demonstrate the proposed method. The substation is composed of three sub-transmission lines, three main transformers, two tie circuit breakers, one 69KV primary bus bar and three 11.4KV secondary bus bars. Each secondary bus contains five radial distribution feeders which are protected by CO relays, LCO relays and reclosers. The main transformers are protected by differential relays. The bus bars are protected by CO and LCO relays and as the back-up protection for each feeder. The three-phase, four-wire distribution system is solidly grounded at substation, with the neutral wire also grounded at each distribution transformer location.

Case 1

Operated relays: CO1-C, LCO1, COM1-C, and LCOM1
Tripped circuit breakers: CBM1
Failure devices: CB1

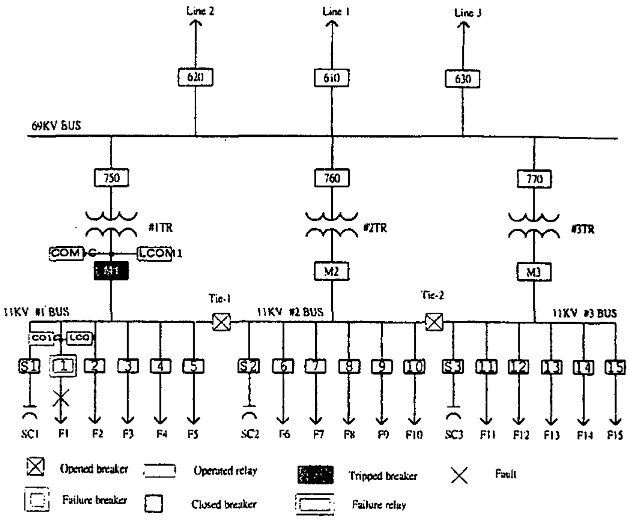


Fig. 4: fault situation of case1

This is a case that a single line-to-ground fault occurs at phase C of feeder section F1 in Fig. 4. The main protective relays "CO1-C" and LCO1 operate. However, the associate breaker, CB1, fails to trip. Owing to the tripping failure of CB1, backup circuit breaker CBM1 is tripped by COM1-C and LCOM1.

First of all, we perform a logic-OR operation into each phase relays of the same feeder (e.g., CO2-A, CO2-B, CO2-C) and the related grounded relay (LCO2) to be an aggregated relay (CO2), i.e., CO2 operated if CO2-A or CO2-B or CO2-C or LCO2 operated. In this manner, we can get the desired CE-Nets. The portion of the CE-Nets, which is associated with this event, is given in Fig. 5. The set of conditions is listed below:

C1: Fault occurs at F1 section
C2: Relay CO1 actuated
C3: Circuit Breaker CB1 tripped
C4: CO1 actuated, but CB1 failed (i.e., $C2 \wedge \overline{C3}$)
C5: Relay COM1 actuated
C6: Circuit Breaker CBM1 tripped
C7: Fault occurs at F2 section
C8: Relay CO2 actuated
C9: Circuit Breaker CB2 tripped
C10: CO2 actuated, but CB2 failed (i.e., $C8 \wedge \overline{C9}$)
C11: Fault occurs at F3 section
C12: Relay CO3 actuated
C13: Circuit Breaker CB3 tripped
C14: CO3 actuated, but CB3 failed (i.e., $C12 \wedge \overline{C13}$)
C15: Fault occurs at F4 section
C16: Relay CO4 actuated
C17: Circuit Breaker CB4 tripped

C18: CO4 actuated, but CB4 failed (i.e., $C16 \wedge \overline{C17}$)
C19: Fault occurs at F5 section
C20: Relay CO5 actuated
C21: Circuit Breaker CB5 tripped
C22: CO5 actuated, but CB5 failed (i.e., $C20 \wedge \overline{C21}$)
C23: Fault occurs at SC1 section
C24: Relay COSC1 actuated
C25: Circuit Breaker CBSC1 tripped
C26: COSC1 actuated, but CBSC1 failed (i.e., $C24 \wedge \overline{C25}$)
C27: Fault occurs at #1BUS section

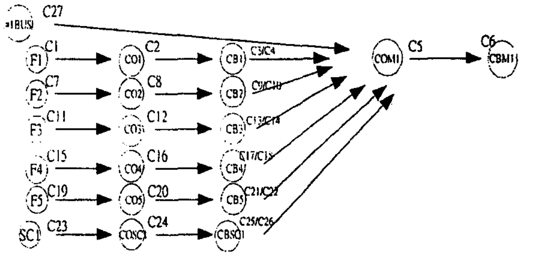


Fig. 5: the associated CE-Nets of case1.

The rule matrix of the associated CE-Net could be found as follows

$$R=\begin{array}{c|ccccccccccccccccccccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 20 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\hline
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
4 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
5 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\
6 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
7 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
8 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
11 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
13 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
14 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
15 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
16 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
17 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
18 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
19 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
20 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
21 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
22 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
23 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
24 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\
26 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
27 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{array}$$

Since, CO1, COM1, CBM1 has actuated, the truth state vector of this case is

$$T=[0\,1\,0\,1\,1\,1\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0]^T$$

and

$$F=[1\,0\,0\,0\,0\,0\,1\,0\,0\,0\,1\,0\,0\,0\,1\,0\,0\,0\,1\,0\,0\,0\,1\,0\,0\,0\,1]^T$$

$$B=[0\,0\,0\,1\,0\,0\,0\,0\,0\,1\,0\,0\,0\,1\,0\,0\,0\,1\,0\,0\,0\,1\,0\,0\,0\,1\,0]^T$$

Consequently, we can get fault candidates for a cause of this fault situation by performing the following matrix operations:

$$\begin{aligned}TV&=R^T\oplus T\\&=[1\,1\,0\,1\,1\,1\,0\,0\,0\,1\,0\,0\,0\,1\,0\,0\,0\,1\,0\,0\,0\,1\,0\,0\,0\,1\,1]^T\end{aligned}$$

and

$$\begin{aligned}FSV&=(TV-T)\odot F\\&=[1\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,1]^T\end{aligned}$$

FSV contains information of all fault section candidates in the way that contains a "1" in its component. By observing the fact that FSV(1)=FSV(27)=1, corresponding to C1 and C27 hold, we can get F1 and #1 BUS as the fault section candidates. Consequently, by checking elimination vector, E

$$E=T\odot B=[0\,0\,0\,1\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0]^T$$

which is not a zero vector. Hence, the candidate #1 BUS is eliminated from fault section candidates due to E(4)=1. Finally, we can easily get the cause of the fault stemmed from section F1 hit by a fault.

Case 2

Operated relays: CO3-A, CO3-B, CO3-C, COM1-A,
COM1-B, COM1-C, CO8-B, CO8-C
Tripped circuit breakers: CBM1, CB8
Failure devices: CB3, LCO8

In this case, a three-phase fault occurs at F3. Relays "CO3-A", "CO3-B" and "CO3-C" operate correctly while breaker "CB3" has failed to be tripped. Owing to the tripping failure of "CB3", the backup breaker "CBM1" is tripped by the operation of relays "COM1-A", "COM1-B" and "COM1-C". Meanwhile, a double-line to ground fault at phases B and C has happened at F8, which causes "CO8-B" and "CO8-C" operate to trip "CB8", but "LCO8" fails. The fault situation is shown in Fig. 6.

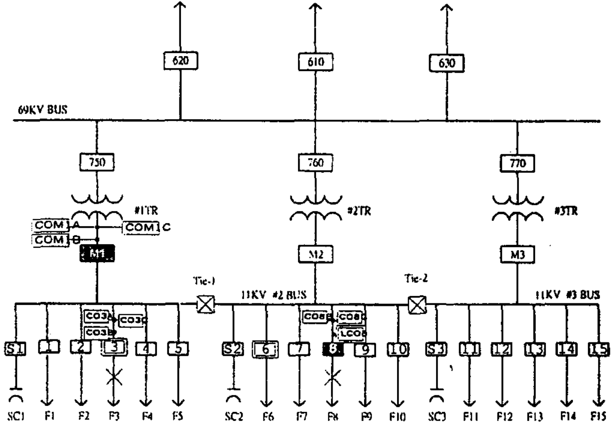


Fig. 6: fault situation of case2

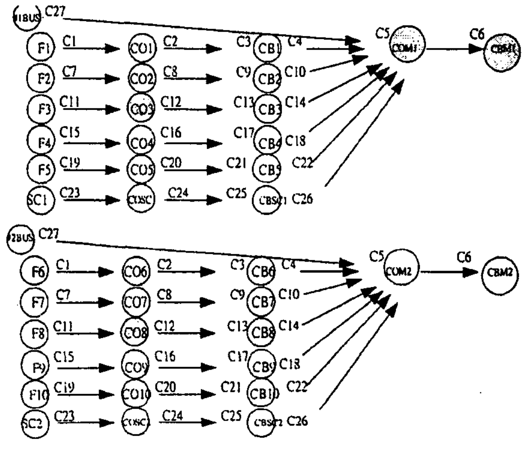


Fig.7: the associated CE-Nets of case2

The associated CE-Nets with this event are shown in Fig. 7. The results of the inference are listed in Table 1. From Table 1, we can easily find that multiple faults occur at F3 and F8.

Table. 1: Results of case2

Conditions hold	Nonzero entries of T	Nonzero entries of TV	Nonzero entries of FSV	Nonzero entries of E	Fault section candidates
C5,C6 C12,C14	5,6,12,14	4,5,6,10,11,12,14,18,22,26,27	11,27	14	*F3 #1BUS
C12,C13	12,13	11,12,13	11	None	*F8

*: Selected fault sections

VI. CONCLUSIONS

As an operator's auxiliary function, this paper has presented a novel approach for estimating fault sections in distribution substations. It is capable of dealing with fault sections for single and multiple faults, even subject to false operations of relays and/or breakers. In many power systems, the states of relays and breakers are on-line available in control center through SCADA systems. Therefore, the proposed method is of much benefit to the operators in analyzing fault situations and as a double-check of operator's decision.

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