Fast Fault Section Estimation in Distribution Substations Using Matrix-Based Cause–Effect Networks

Wen-Hui Chen, Chih-Wen Liu, and Men-Shen Tsai

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 rule matrix transformation techniques are presented. The matrix based inference procedures are proposed to estimate the possible fault sections through simple matrix operations by transforming the established CE-Nets into matrix forms. The method is superior to existing production systems in the inference speed and the process of implementation. By testing on a typical Taiwan Power Company's (Taipower) secondary substation, the experimental results show that the effectiveness of the proposed method even for the fault domains involving multiple faults and failure operations of protective devices. Moreover, it is easy to implement and transplant into different substations.

Index Terms—Cause-effect network, fault diagnosis, rule matrix.

I. INTRODUCTION

WITH recent advances in computer and communication technologies, the computer-based Supervisory Control And Data Acquisition (SCADA) systems are increasingly used in the modern electric utility field. The ultimate goal for a power system is to supply a reliable and stable power to the customs. However, it is inevitable that disturbances such as lightning strokes, collisions and equipment failures will occur. In case of a fault does occur, it is imperative to restrict the impact of outages to the minimum and to restore the faulted facilities as quickly as possible. This requires the location and nature of the fault first be identified, which is the main issue of fault diagnosis in power systems. Taiwan Power Company (TPC) has implemented a Hierarchical Dispatch and Control System (HDCS) to meet the requirements of Taiwan's highly industrialized society in a better quality and higher reliability fashion. The HDCS is a three-level control system, which comprises a CDCS (Central Dispatch and Control System), six ADCSs (Area Dispatch and Control System) and nineteen DDCSs (Distribution Dispatch and Control System). In a DDCS control center, on average, the operator is responsible for more than fifteen unmanned secondary substations simultaneously. In normal operating conditions, operators can properly

deal with various situations. Once faults appear, the operators may find it difficult to analyze the faults and take appropriate actions in the overwhelming alarm messages. This task become increasingly complex if multiple faults have occurred or some pieces of equipment have malfunctioned. Our research was motivated by the result of discussing with the operators in Keelung DDCS located in northern Taiwan. An opinion was expressed that a fault diagnosis tool ought to be developed as an operator's aid function in control center.

In recent decades, a number of technical papers with different methods [1]–[8], such as Expert Systems (ES) and Artificial Neural Networks (ANN) have been successfully applied for power system fault diagnosis. However, there are still some weak points to be improved in conventional methods. For example, the inference speed of rule-based ES is slow in real-time environments due to its sequentially searches for the solution by pattern matching to the hypotheses. As to the ANN techniques, some problems still remain unsolved in practical application so far, such as slow convergence in the training process, and the determination of the network parameters. Besides, neither the cause nor the algorithm for the diagnosis could be determined by the ANN. In [9], the knowledge representations and inference procedures using CE-Nets and marker propagation were presented. However, the conventional inference algorithm has no solution in some situations.

In this paper, a matrix-based inference mechanism is proposed to overcome the aforementioned drawback and provide a better way to the implementation issue. This paper focuses on fault diagnosis for automated substations and assumes that the information on the status of relays and circuit breakers is available from SCADA systems subjected to the following problem domains:

- 1) Single fault without failure device.
- 2) Single fault with more than one failure device.
- 3) Multiple faults without failure device.
- 4) Multiple faults with more than one failure device.

A section of the substation here refers as a feeder, a bus bar or a transformer, which can be separated by breakers. Prior to dealing with such a fault diagnosis problem, the following assumptions are also given:

- 1) The action of relays is caused by the fault.
- 2) All relays and circuit breakers are in their final states.
- 3) Operations of any devices are known through SCADA systems and updated in the database.

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Fig. 1. (a) Protected-by arc. (b) Cause arc. (c) Backup-by arc.

Fig. 2. A simple model distribution system.

II. CAUSE-EFFECT NETWORK

A CE-Net is a graphic-modeling tool for representing the causality between faults and actions of protective devices, including the three kinds of nodes below:

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

In addition, there are three kinds of arcs as shown in Fig. 1.

- 1) *Protected-by*
Means that a fault in section A causes the action of relay B.
- 2) *Cause*
Means that the action of relay A causes the trip of circuit breaker B.
- 3) *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. 2, 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

Fig. 3. CE-Nets of model system.

Fig. 4. (a) Relation of protected-by arc. (b) Relation of cause arc. (c) Relation of backup-by arc.

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. 3. After considering all the possible faulted sections, we can get the CE-Nets of the model system as shown in Fig. 3.

III. MATRIX REPRESENTATION OF CE-NETS

Once the CE-Nets are established, the next step of the proposed method is to transform them to the rule matrix. Suppose that C_i and C_j are conditions of nodes in given CE-Nets, a rule matrix R with entry $R(i, j) = 1$ means that the truth of condition C_j implies the truth of condition C_i . On the other hand, $R(i, j) = 0$ indicates that there is no implication between C_i and C_j . The diagonal of R contains all ones by reflexivity and with Boolean entries (0 or 1) through three relations as shown in Fig. 4.

To explain matrix representation of the CE-Nets, Fig. 5 is used for illustration.

By observing the connection of each nodes, the rule matrix of Fig. 5 can therefore be constructed as

$$R = \begin{bmatrix} C1 & C2 & C3 & C4 & C5 & C6 & C7 & C8 & C9 & C10 & C11 \\ \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} & \begin{matrix} C1 \\ C2 \\ C3 \\ C4 \\ C5 \\ C6 \\ C7 \\ C8 \\ C9 \\ C10 \\ C11 \end{matrix} \end{bmatrix}$$

Fig. 5. CE-Nets for illustration of matrix representation.

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 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

Prior to developing the inference procedures, we define the following column vectors for matrix operations.

- Truth state vector (T)

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

where C_i is a condition of nodes in given CE-Nets.

- Fault node vector (F)

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

- Backup condition vector (B)

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

- Transformation Vector (TV)

$$TV \equiv R^T \oplus T$$

where " $\oplus$ " is the multiplication of two matrices, which replace real multiplication and addition with AND and OR, respectively. The operation process called truth state transformation.

For example,

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

- Fault Section Vector (FSV)

$$FSV = (TV - T) \odot F$$

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

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)

$$E \equiv T \odot B.$$

The transpose of a rule matrix corresponds to the reversal of all arrows in the associated CE-Nets and takes a truth state of given results backward into an abduced state of cause [10]. Since the truth state transformation preserves truth states and propagates truths, the transformation vector (TV) contains the information of all possible causes. In order to pick up a possible fault section, we define the fault section vector (FSV) to get rid of the result states and filter the state of nonfault section nodes. If the elimination vector (E) is not a zero vector, it means that there must be a backup relay actuated. In such situation, the main protective section of backup relays should be eliminated from fault section candidates. The proposed inference procedures are achieved through the following steps:

Steps of Inference:

- Step 1) Establishing rule matrix, R , of given CE-Nets.
- Step 2) Deriving truth state vector, T , from fault information.
- Step 3) Calculating transformation vector, TV.
- Step 4) Calculating fault section vector, FSV.
- Step 5) Selecting fault section candidates from entries comprising "1" of FSV.
- Step 6) Calculating elimination vector, E . If E is a zero vector, the fault section candidates selected from step 5 are chosen as the fault sections. On the other hand, if E is not a zero vector, the main protective section of the backup relay that corresponding to nonzero entries of E should be eliminated from fault section candidates and the rest of candidates are chosen as the fault sections.

V. EXAMPLES

We use a realistic Taipower's secondary substation to demonstrate the proposed method. Two case studies of the example substation are presented without loss of generality.

The substation is composed of three sub-transmission lines, three main transformers, two tie circuit breakers, one 69 KV primary bus bar and three 11.4 KV 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

Fig. 8. Fault situation of case 2.

In this case, #2 TR has de-energized for maintenance and Tie-1 breaker is in the closing status. A three-phase fault occurs at F3. Relays “CO3-A,” “CO3-B” and “CO3-C” operate correctly while breaker “CB3” has failed to trip. Owing to the tripping failure of “CB3,” the backup breaker “CBM1” is tripped by the operation of relays “COM1-A,” “COM1-B”

Fig. 9. The associated CE-Nets of case 2.

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. 8.

The associated CE-Nets of this event are shown in Fig. 9. The results of the inference are listed in Table I. From Table I, we

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
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	1	0	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	1	0	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	1	1	0	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	1	1	0	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

TABLE I
RESULTS OF CASE 2

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,C37 C38	5,6,12,14, 37,38	4,5,6,10,11, 12,14,18,22, 26,27,31,35, 36,37,38,39, 43,47,51	11,27,36	14	*F3 #1BUS *F8

*: selected fault section

can find that fault sections F3 and F8 are selected, i.e., multiple faults at F3 and F8 are estimated.

VI. CONCLUSION

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. The proposed method has been observed to have the following features:

- Fast inference speed.
- Plainness of knowledge representation.
- Simplicity in inference procedures.
- Ease of implementation and data base maintenance.

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