Implementing Fuzzy Reasoning Petri-nets for Fault Section Estimation

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***Abstract*— Fuzzy Reasoning Petri-nets is a promising technique to tackle the complexities of power system fault section estimation. This paper addresses several key issues in implementing Fuzzy Reasoning Petri-nets for fault section estimation, which include optimal design of structure of diagnosis models to avoid large matrix size, utilization of fuzzy logic parameters to effectively handle uncertainties, realization of matrix execution algorithm to achieve parallel reasoning and adaptability, and integration of more reliable input data to enhance estimation accuracy. Case studies are presented to demonstrate the estimation capability under complex scenarios. An implementation solution residing in a control center is proposed.**

***Index Terms*— Fault section estimation, Fuzzy reasoning, Petri-nets, Power systems, Relays, SCADA systems.**

I. Introduction

A POWER system is composed of lots of sections such as generators, transformers, bus bars and transmission lines. These sections are protected by protection systems comprising protective relays, circuit breakers and communication equipments. When a fault occurs on a certain section of the power system, the protection devices will reach certain statuses accordingly. To identify the faulted section of a power system based on a set of observed statuses of protection devices is called fault section estimation. This is a vital task for system operators because it provides the most fundamental information for restorative actions. The task is stressful, time consuming, and the accuracy is restricted when multiple faults, failures of protection devices, and false data are involved. When all mix up, a large number of scenarios can be hypothesized and the possibility of each scenario needs to be examined. Complexity of fault section estimation increases significantly.

Since the late eighties, various fault section estimation applications based on Expert System (ES) technique have been reported in literature [1]–[4]. ES technique is suited for a diagnosis problem like fault section estimation because it mimics the behaviors of fault analysis experts to perform fact-rule comparisons and consequent search steps. Coupled with ES technique, Fuzzy Logic (FL) technique is also employed to solve the problem of fault section estimation, as reported in the literature [5], [6]. FL technique offers a convenient means for modeling inexactness and uncertainties, hence a powerful solution to handle the uncertainties due to unexpected operations of protective devices and false data. The major drawbacks of ES based techniques are burdensome procedures of knowledge acquisition and knowledge base maintenance, and slow response time due to conventional knowledge representation and inference mechanism.

In recent years, Petri-nets (PN) technique, which possesses the characteristics of graphic discrete event representation and parallel information processing, has gained researchers' strong interests [7]–[10]. References [7], [8] model fault clearance process as discrete events using Petri-nets and utilize the reversed Petri-nets models for fault section estimation. Such models take circuit breaker statuses as inputs. Similarly, reference [9] proposes Petri-nets models to estimate fault sections based on protective relay trip operations. Reference [10] augments Petri-nets with additional places to introduce net redundancy. Coding theory is applied to detect place faults which represent all kinds of errors during fault clearance process. These solutions, which are based on discrete event view of Petri-nets, have several limitations. The number of initial inputs are limited and it is difficult to model inexactness and uncertainties. Consequently, to accurately identify fault sections under complex circumstances, substantial heuristic rules and information are additionally required.

It has been proven that fuzzy rule-based reasoning can be realized through Petri-nets formalism [11]–[13]. Fuzzy Reasoning Petri-nets (FRPN) gains the advantages of Expert System and Fuzzy Logic, as well as parallel information processing. Reference [14] applies the formalism established in [11] to solve the problem of fault section estimation. It builds graphical Petri-nets models which represent fuzzy reasoning rules and validates the reasoning process. The paper does not address the optimal design of the structure of FRPN diagnosis models and the matrix reasoning execution algorithm, which are two key factors for implementation of FRPN for fault section estimation. The structure of FRPN diagnosis models affects diagnosis accuracy as well as implementation performance. The matrix reasoning execution algorithm is the core of parallel processing capability of FRPN.

Our paper presents a formal definition of FRPN and discusses several key issues in implementation of FRPN for fault section estimation. First, the optimal design of structure of FRPN diagnosis models is detailed and the advantage over the structure adopted in [14] is addressed. Then, the graphical FRPN models built based on the optimal structure are illustrated and the utilization of fuzzy logic parameters to effectively tackle uncertainties is discussed. Following that, a matrix reasoning execution algorithm of FRPN is introduced. The algorithm is exemplified by matrix rule representation and reasoning execution for an FRPN diagnosis model which takes data from remote terminal units (RTU) of supervisory control and data acquisition systems (SCADA) as inputs.

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Integration of logic operand data of digital protective relays as additional inputs to enhance the estimation accuracy is further discussed. That is followed by case studies on a 14-bus power system model which demonstrate the estimation capability under various scenarios. Finally our paper proposes a control center implementation solution which is adaptive to changes of input data, as well as power system and protection system configuration.

II. Fuzzy Reasoning Petri-nets

A. Definition

A Fuzzy Reasoning Petri-net (FRPN) can be defined as an 8-tuple [13]:

$$(P, R, I, O, H, \theta, \gamma, C)$$

where

1) $P = \{p_1, p_2, ..., p_n\}$ is a finite set of places or called propositions.
2) $R = \{r_1, r_2, ..., r_m\}$ is a finite set of transitions or called rules.
3) $I : P \times R \longrightarrow \{0, 1\}$ is an $n \times m$ input matrix defining the directed arcs from propositions to rules. $I(p_i, r_j) = 1$, if there is a directed arc from p_i to r_j, and $I(p_i, r_j) = 0$, if there is no directed arcs from p_i to r_j, for $i = 1, 2, ..., n$, and $j = 1, 2, ..., m$.
4) $O : P \times R \longrightarrow \{0, 1\}$ is an $n \times m$ output matrix defining the directed arcs from rules to propositions. $O(p_i, r_j) = 1$, if there is a directed arc from r_j to p_i, and $O(p_i, r_j) = 0$, if there is no directed arcs from r_j to p_i, for $i = 1, 2, ..., n$, and $j = 1, 2, ..., m$.
5) $H : P \times R \longrightarrow \{0, 1\}$ is an $n \times m$ matrix defining the complementary arcs from propositions to rules. $H(p_i, r_j) = 1$, if there is a complementary arc from p_i to r_j, and $H(p_i, r_j) = 0$, if there is no complementary arcs from p_i to r_j, for $i = 1, 2, ..., n$, and $j = 1, 2, ..., m$.
6) θ is a truth degree vector. $\theta = (\theta_1, \theta_2, ..., \theta_n)^T$, where $\theta_i \in [0, 1]$ means the truth degree of p_i, $i = 1, 2, ..., n$. The initial truth degree vector is denoted by θ^0.
7) $\gamma : P \longrightarrow \{0, 1\}$ is a marking vector. $\gamma = (\gamma_1, \gamma_2, ..., \gamma_n)^T$. $\gamma_i = 1$, if there is a token in p_i, and $\gamma_i = 0$, if p_i is not marked. An initial marking is denoted by γ^0.
8) $C = diag\{c_1, c_2, ..., c_m\}$. c_j is the confidence of r_j, $j = 1, 2, ..., m$.

The 5-tuple (P, R, I, O, H) is the basic FRPN structure that defines a directed graph. The updates of the truth degree vector θ through execution of a set of rules describe the dynamic reasoning process of the modeled system. If the truth degree of a proposition is known at a certain reasoning step, a token is assigned to the corresponding proposition, which is associated with the value between 0 and 1. The token is represented by a dot. When a proposition p_i has no token, which means that the truth degree is unknown at that step, $\theta_i = 0$.

B. Execution Rules

In order to describe the execution rules of a FRPN, the following operators are used:

1) $\bigoplus$: $\mathbf{A} \bigoplus \mathbf{B} = \mathbf{D}$, where $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{D}$ are all $m \times n$-dimensional matrices, such that $d_{ij} = max\{a_{ij}, b_{ij}\}$.
2) $\bigotimes$: $\mathbf{A} \bigotimes \mathbf{B} = \mathbf{D}$, where $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{D}$ are $(m \times p)$, $(p \times n)$, $(m \times n)$-dimensional matrices respectively, such that $d_{ij} = max_{1 \le k \le p}(a_{ik} \cdot b_{kj})$.

The execution rules include enabling and firing rules.

1) A rule $r_j \in R$ is enabled if and only if p_i is marked, or $\gamma_i = 1$, $\forall p_i \in \{\text{input propositions of } r_j\}$.
2) Enabled at marking γ, r_j firing results in a new γ'
$\gamma'(p) = \gamma(p) \bigoplus O(p, r_j), \qquad \forall p \in P.$
The truth degree vector changes from θ to θ'
$\theta'(p) = \theta(p) \bigoplus c_j \cdot \rho_j \cdot O(p, r_j), \qquad \forall p_i \in P$
where
$\rho_j = min_{p_i \in \dot{r_j}}\{x_i | x_i = \theta_i if I(p_i, r_j) = 1;$
$\quad x_i = 1 - \theta_i if H(p_i, r_j) = 1\}$
and
$\dot{r_j} = \{p_i | I(p_i, r_j) = 1 or H(p_i, r_j) = 1, p_i \in P\}$
3) All the enabled rules can fire at the same time. A firing vector μ is introduced such that $\mu_j = 1$ if r_j fires. After firing a set of rules, the marking and truth degree vectors of the FRPN become

$$\gamma' = \gamma \oplus [O \otimes \mu] \tag{1}$$

$$\theta' = \theta \oplus [(O \cdot C) \otimes \rho] \tag{2}$$

where
$\rho = [\rho_1, \rho_2, ..., \rho_m]^T$, which is called control vector. $\mu : T \longrightarrow \{0, 1\}$ is the firing vector. $\mu = (\mu_1, \mu_2, ..., \mu_m)^T$.

III. Implementation of FRPN for Fault Section Estimation

A. Power System Under Study

In this section, a 14-bus power system as shown in Fig. 1 is used for the study of fault section estimation problem. The system consists of 34 sections, including 14 buses and 20 transmission lines. The buses are denoted as Bnn. The transmission lines are denoted as Lnnmm. The protection system of the 14-bus system consists of 174 protection devices, including 40 circuit breakers, 40 main transmission line relays, 40 primary backup transmission line relays and 40 secondary backup transmission line relays and 14 bus relays.

To explain the configuration and denotation of the protection system, a portion of the 14-bus power system is taken as

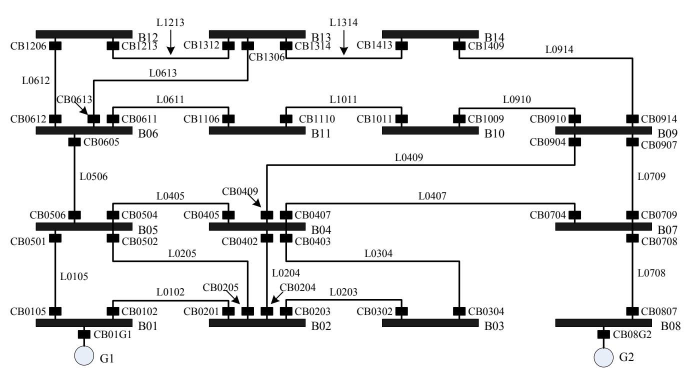

Fig. 1. A 14-bus power system model

an example as shown in Fig. 2. The portion includes a transmission line L1314, and its adjacent bus B13, B14 and adjacent transmission lines L1213, L0613, L0914. The main transmission line relay MLR1314 has forward protection zone and protects the entire line L1314. It will operate to trip its associated circuit breaker CB1314 to clear a fault on the line L1314. The bus relay BR13 protects the bus B13. It will operate to trip the circuit breakers CB1312, CB1306, CB1314 if a fault occurs on the bus B13. The primary backup transmission line relay BLR1314 is the local backup of the relay MLR1314 and has the same protection zone. If the fault clearance by the relay MLR1314 fails, the relay BLR1314 will operate to trip the circuit breaker CB1314 to clear the fault. Secondary backup transmission line relays SLR1213, SLR0613 are the remote backup of the relays MLR1314, BLR1314. If the fault clearance by both the relays MLR1314, BLR1314 fails, they will operate to trip their associated circuit breakers CB1213, CB0613 respectively to clear the fault. The relays SLR1213, SLR0613 are also the remote backup of the relay BR13. If the fault clearance by the relay BR13 fails, they will operate to trip circuit breakers CB1213, CB0613 respectively to clear the fault. The relays MLR1413, BLR1413, SLR0914, BR14 and circuit breakers CB1413, CB1409, CB0914 have similar roles in protecting the line L1314 and bus B14. The configuration and denotation of the protection system for other sections of the 14-bus power system are similar.

B. FRPN Diagnosis Model

When one or more faults occur on certain sections of the power system, protection devices will reach certain statuses accordingly. The observed relay trip signals and circuit breaker status signals obtained from RTUs of SCADA systems are used as inputs for estimation of the faulted sections. The strategy is to build one FRPN diagnosis model for each section of the power system. Each model establishes reasoning from a set of SCADA data to the conclusion of fault occurrence on its associated section with certain truth degree value. In case of single fault, the conclusion with the highest truth degree value is the final conclusion. In case of multiple faults, the several conclusions with the highest truth degree values which are greater than a threshold are regarded as the final conclusions.

To build the FRPN diagnosis models, several issues should be carefully considered. First, a sound methodology for structure design needs be adopted to achieve good diagnosis performance while keeping the model size small. Second, to deal with failures of protective devices, backup protection operations need to be considered in the models. Third, to tackle false data problem introduced by defects of protection devices, measurement systems or communication systems, fuzzy logic concept needs to be effectively utilized.

We use backward reasoning concept to structure the FRPN diagnosis models and generalize the design for transmission lines and buses [15]. Fig. 3 and Fig. 4 illustrate backward reasoning concept for structuring transmission line and bus diagnosis models respectively. The 'AND-OR' structure concisely represents all the possible combinations of main, primary backup and secondary backup protection operations for inferring a fault. Compared with the 'OR-AND' "enumeration" type of structure used in [14], our proposed structure effectively covers more scenarios with smaller number of rules, which will eventually achieve higher diagnosis accuracy with smaller size of Petri-nets matrix. For example, for inferring a bus fault on a bus with 5 circuit breakers connected, Fig. 4 represents all the 32 (2^5) different combinations of protection operations (each circuit breaker is associated with main bus protection operation or secondary backup protection operation). The model shown in Fig. 4(b) in [14] only enumerates a small number of all the combinations of protection operations. In the scenarios of multiple failures of circuit breakers which the model does not represent, it is not able to identify the bus fault. If the model is expanded to enumerate all the combinations of protection operations, it will result in very large petri-nets matrix size.

Based on the proposed structure, all the FRPN diagnosis models are developed. As examples, Fig. 5 and Fig. 6 show the FRPN models for the transmission line L1314 and bus B13 in Fig. 1 respectively.

In Fig. 5, the places p_1, p_2, ..., p_{12} represent the input propositions, which are the operations of protection devices associated with the transmission line L1314. Initially all of these places contain a token, which means that the truth degrees of these propositions are known. Each such proposition will be assigned a truth degree value describing the certainty of observation of the operation of the protection device. Under such an assumption, if the operation of a protection device is actually observed, the proposition will have a truth

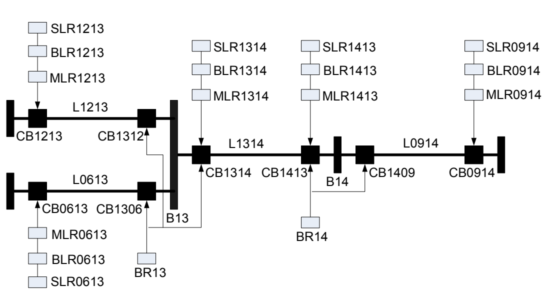

Fig. 2. An example of protection system configuration

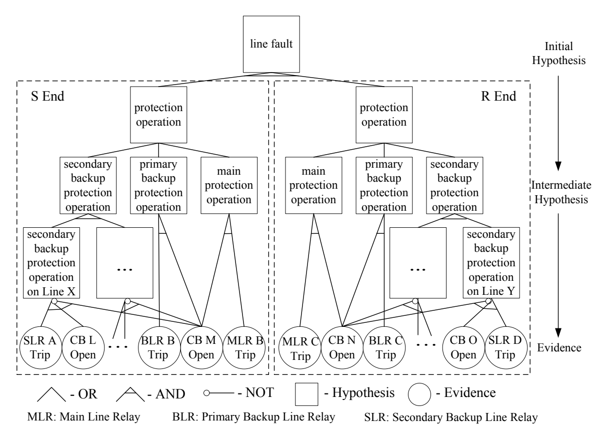

Fig. 3. Backward reasoning concept for structuring transmission line diagnosis models

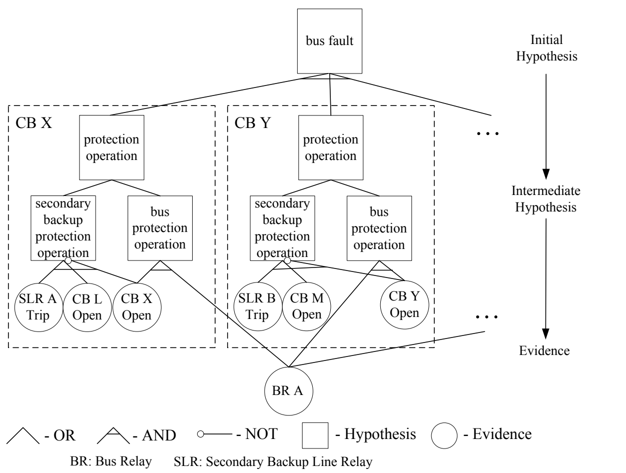

Fig. 4. Backward reasoning concept for structuring bus diagnosis models

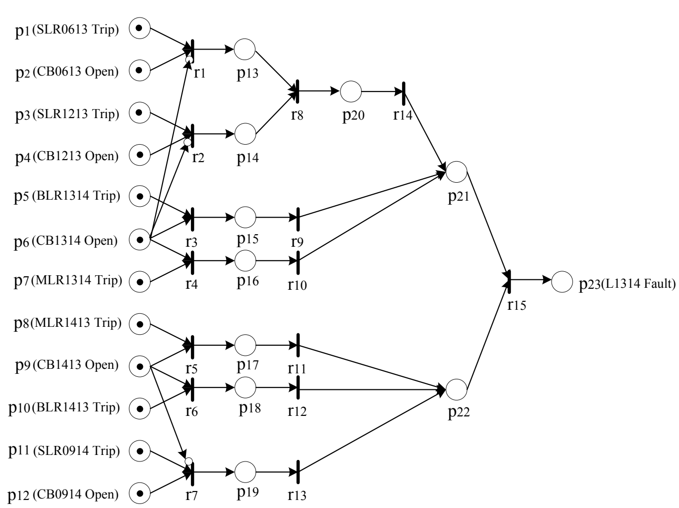

Fig. 5. A FRPN model for L1314 fault based on SCADA data

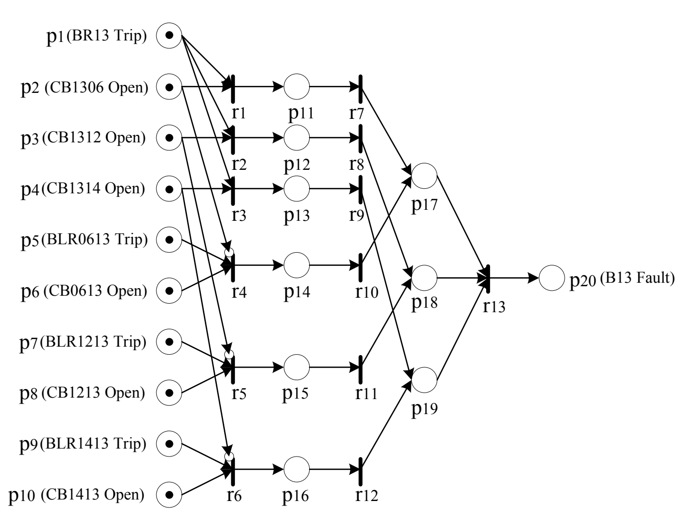

Fig. 6. A FRPN model for B13 fault based on SCADA data

degree value θ_i which is bigger than 0. On the contrary, if the operation of the protection device is not observed, the proposition will have a 0 truth degree value. θ_i can be given by experience based on the reliability of the indication logic of the protection device, measurement system and communication system. In this example, θi will be given the same value of 0.9.

The places p_{13}, p_{14}, ..., p_{22} represent the propositions which are intermediate reasoning results. The place p_{23} represents the output proposition "a fault exists on the transmission line L1314".

The transitions r_1, r_2, ..., r_{15} represent rules in which antecedent propositions implicate consequent propositions. Each rule r_j is associated with a certainty factor c_j, which describes the confidence level of the rule. $c_j, j = 1, 2, ..., 7$ can be given by experience based on the reliability of relays. Usually a main relay has higher reliability than that of a primary backup relay. A primary backup relay has higher reliability than that of a second backup relay. In this example, c_1, c_2, c_3, c_4, c_5, c_6, c_7 will be given the values 0.7, 0.7, 0.8, 0.9, 0.9, 0.8, 0.7 respectively. $c_j, j = 8, 9, ..., 15$ will be given the same value 1.0.

It should be mentioned that from p_6 to r_1 and from p_6 to r_2, there are two complementary arcs, which means that if the opening of the circuit breaker CB1314 is observed, the operation of the corresponding secondary backup protection should be discredited. On the contrary, if the opening of the circuit breaker CB1314 is not observed, the operation of the corresponding secondary backup protection should be credited. The complementary arc from p_9 to r_7 have the same meaning.

We use a "weighted average" operation to replace the "minimum" operation defined in [13] when calculating the truth degree value of a consequent proposition from the truth degree values of its antecedent propositions. Fig. 7 illustrates the operation for r_1 in Fig. 5. The "weighted average" operation has two benefits.

First, the relative significance of antecedent propositions in implicating the consequent proposition is recognized by the weights of antecedent propositions. This is particularly meaningful when the cause-effect relation among antecedent propositions is considered. In our assumption, circuit breaker opening is the effect of relay trip. The "circuit breaker opens" proposition is generally given larger weight than that of the "relay trips" proposition because circuit breaker opening indicates the completion of a protection operation more directly. For example, regarding the rule r_3 in Fig. 5, the proposition p_5 "BLR1314 Trip" will be given a weight 0.4; the proposition p_6 "CB1314 Open" will be given a weight 0.6.

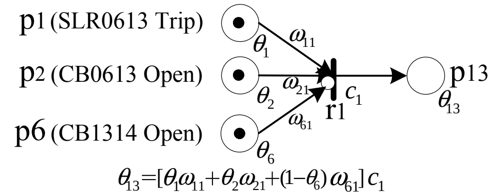

Fig. 7. An example of "weighted average" operation

Second, the false data problem is effectively handled by averaging the truth degree values of antecedent propositions. For example, when the relay MLR1314 trips and the circuit breaker CB1314 opens as a consequence of a fault on the line L1314, and "MLR1314 Trip" is not observed, p_{15}, which stands for "main protection operates", will still get a moderate truth degree value instead of 0, hence a moderate truth degree value for the final conclusion. It is apparent that the larger the number of input data, the impact of false data is more effectively countered.

C. Matrix Execution Algorithm

The parallel reasoning process of FRPN is implemented by matrix execution. Reference [13] presents an algorithm based on the execution rules discussed in Section II. We modifies the algorithm to accommodate the "weighted average" operation.

(1) and (2) in Section II show that as long as μ and ρ are known, the next step marking and truth degree vectors can be derived from the current values. To obtain μ and ρ, an 'neg' operator is used as follows:

$neg\gamma^k = 1_m - \gamma^k = \overline{\gamma^k}$

$neg\theta^k = 1_m - \theta^k = \overline{\theta^k}$

where $1_m = (1, 1, ..., 1)^T$.

μ^k is calculated as follows:

$$\mu^k = \overline{(I+H)^T \otimes \overline{\gamma^k}} \tag{3}$$

where γ^k is the marking.

ρ^k is calculated as follows:

$$\rho^k = ((I^T .* W^T) \cdot \theta^k + (H^T .* W^T) \cdot \overline{\theta^k}) .* \mu^k \tag{4}$$

where W is the weight matrix. The $\cdot*$ operator is defined as follows:

$\cdot*$: $\mathbf{A} \cdot * \mathbf{B} = \mathbf{D}$, where $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{D}$ are all $m \times n$-dimensional matrices, such that $d_{ij} = a_{ij} \cdot b_{ij}$.

From (1) and (3), we can get

$$\gamma^{k+1} = \gamma^k \oplus [O \otimes \overline{(I+H)^T \otimes \overline{\gamma^k}}] \tag{5}$$

From (2), (3) and (4), we can get:

$$\theta^{k+1} = \theta^k \oplus [(O \cdot C) \otimes (((I^T .* W^T) \cdot \theta^k + (H^T .* W^T) \cdot \overline{\theta^k}) .* \mu^k)] \tag{6}$$

To summarize, the matrix execution algorithm can be described as follows:

1) Read initial inputs I,O,H,C,γ^0, and θ^0.
2) Let $k = 0$.
3) Compute γ^{k+1} from γ^k according to (5); Compute θ^{k+1} from θ^k according to (6).
4) If $\theta^{k+1} \neq \theta^k$ or $\gamma^{k+1} \neq \gamma^k$, let $k = k + 1$, and return to Step 3; Otherwise, the reasoning is over.

We take the reasoning process for the transmission line L1314 diagnosis model shown in Fig. 5 as an example. The matrix representation of the model is given in Fig. 8.

$$I = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\quad
O = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

$$H = \begin{bmatrix}
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 & 0 & 0 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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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 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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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 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\quad
W = \begin{bmatrix}
.4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
.3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & .4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & .3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & .4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
.3 & .3 & .6 & .6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & .4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & .4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & .6 & .6 & .3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & .4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & .4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & .3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & .5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & .5 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .5 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .5 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

$$C = \begin{bmatrix}
0.85 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.85 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.95 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.95 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.85 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

Fig. 8. Matrix representation for the FRPN model for L1314 fault

When a fault occurs on the line L1314, its associated protection system operated to respond to the fault. The following signals are observed in SCADA data: SLR0613 Trip, CB0613 Open, SLR1213 Trip, CB1213 Open, BLR1314 Trip, MLR1314 Trip, MLR1413 Trip and CB1413 Open. γ^0 and θ^0 are given as:

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

$\theta^0 = [\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ ]^T$

The first reasoning step will result in

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

$\theta^1 = [\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0.791\ 0.791\ 0.324\ 0.342\ 0.855\ 0.486\ 0.0260\ 0\ 0\ 0\ 0\ ]^T$

The second reasoning step will result in

$\gamma^2 = [\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ ]^T$

$\theta^2 = [\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0.791\ 0.791\ 0.324\ 0.342\ 0.855\ 0.486\ 0.026\ 0.791\ 0.342\ 0.855\ 0\ ]^T$

The third reasoning step will result in

$\gamma^3 = [\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ ]^T$

$\theta^3 = [\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0.791\ 0.791\ 0.324\ 0.342\ 0.855\ 0.486\ 0.026\ 0.791\ 0.791\ 0.855\ 0.599\ ]^T$

The final reasoning step will result in

$\gamma^4 = [\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ ]^T$

$\theta^4 = [\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0.791\ 0.791\ 0.324\ 0.342\ 0.855\ 0.486\ 0.026\ 0.791\ 0.791\ 0.855\ 0.823\ ]^T$

So the conclusion will be that a fault occurred on the transmission line L1314 with a truth degree value 0.823.

Taking the same example as above, if MLR1413 Trip is missing in the SCADA data due to data transmission error, the conclusion will be that a fault occurred on the transmission line L1314 with a truth degree value 0.652.

D. Improvement by Digital Protective Relay Data

In a digital protective relay, the pickup and operation information of protection elements is usually in the form of logic operands [16], [17]. These logic operands are in essence digital bits, which can be directly transmitted in the form of register values via a digital communication system. The pickup and operation logic operands are more reliable than SCADA data because they are more redundant and have less uncertainty than relay trip signals and circuit breaker status signals. They can be utilized to improve the accuracy of fault section estimation based on SCADA data.

Fig. 9 illustrates how the pickup and operation information is added into the FRPN model built for diagnosing a fault on the transmission line L1314.

The matrix representation of the FRPN model described by Fig. 9 can be easily generated based on the matrix representation of the FRPN model described by Fig. 5. The updated matrices I, O, H, W are given in Fig. 10. There is no change on matrix C. The weight assignment in W is adjusted to reflect the relative significance of input signals in determination of the occurrence of a protection operation. The operation of relay element has the largest weight and the pickup of relay element has the second largest weight. The relay trip and the circuit breaker opening have smaller weights. When the absence of the circuit breaker opening for the main protection and primary

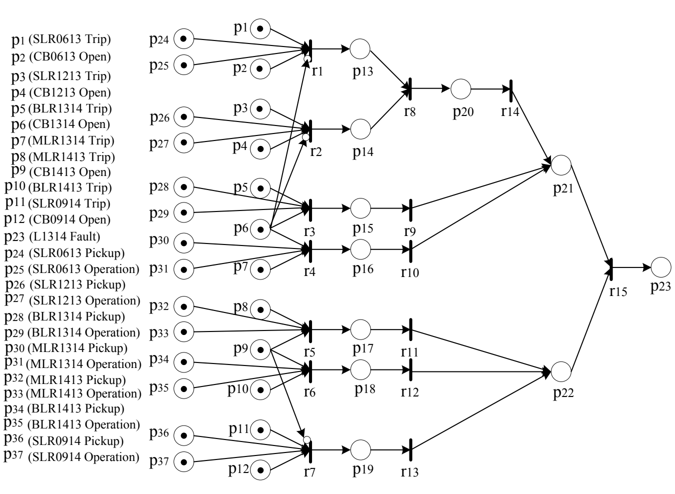

Fig. 9. A FRPN model for L1314 fault based on SCADA and digital protective relay data

$$I = \begin{bmatrix}
1 & 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 & 0 & 0 \\
0 & 1 & 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 & 0 \\
0 & 0 & 1 & 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 \\
0 & 0 & 0 & 1 & 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 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 & 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 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
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 & 0 & 0 & 0 \\
1 & 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 & 0 & 0 \\
0 & 1 & 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 & 0 \\
0 & 0 & 1 & 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 \\
0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\quad
O = \begin{bmatrix}
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 & 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 & 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 & 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 & 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 & 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 & 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 & 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 & 0 \\
0 & 0 & 1 & 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 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 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 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 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 & 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 & 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 & 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 & 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 & 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 & 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 \\
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 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

$$H = \begin{bmatrix}
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 & 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 & 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 & 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 \\
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 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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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 & 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 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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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 & 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 & 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 & 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 & 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 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\quad
W = \begin{bmatrix}
.05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
.3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & .05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & .3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & .05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
.3 & .3 & .6 & .6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & .05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & .05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & .6 & .6 & .3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & .05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & .05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & .3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & .5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & .5 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 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 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .5 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .5 \\
0 & 0 & 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 \\
.2 & 0 & 0 & 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 & .2 & 0 & 0 & 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 & .2 & 0 & 0 & 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 & .2 & 0 & 0 & 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 & .2 & 0 & 0 & 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 & .2 & 0 & 0 & 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 & .2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

Fig. 10. Updated matrix representation for the FRPN model for L1314 fault

backup protection is taken into consideration of the secondary backup protection, it has the largest weight.

We take the same example as in previous section. When a fault occurs on the transmission line L1314, its associated protection system operated to respond to the fault. In addition to the observed SCADA data, the following relay signals are also observed: SLR0613 Pickup, SLR0613 Operation, SLR1213 Pickup, SLR1213 Operation, BLR1314 Pickup, BLR1314 Operation, MLR1314 Pickup, MLR1314 Operation, MLR1413 Pickup, MLR1413 Operation, BLR1413 Pickup, SLR0914 Pickup. Since the relay data are more reliable than the SCADA data, they are given a larger truth value 0.98. γ^0

and θ^0 are given as:

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

$$\theta^0 = [\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0\ 0.98\ 0\ ]^T$$

The final conclusion will be that a fault occurs on the transmission line L1314 with a truth degree value 0.848.

Taking the same example as above, if MLR1413 Trip is missing in the SCADA data due to data transmission error while MLR1413 Pickup and MLR1413 Operation are observed, the conclusion will be that a fault occurs on the transmission line L1314 with a truth degree value 0.827.

IV. Case Study

Based on the approach introduced by the authors earlier [18], a power system/protection system interactive simulation environment for the case study has been developed according to the power system shown in Fig. 1 and its corresponding protection system configuration. The environment enables one to set up fault scenarios, insert user-defined errors, and generate SCADA data and relay data.

A. Test Cases and Results

Case 1: A permanent fault occurred on the transmission line L0910 at 0.05 second. All the protection devices operated correctly. No false data occurred. The observed SCADA data are listed in Table I. The observed relay data are listed in Table II.

Based on the SCADA data in Table I, the only candidate for the fault section is estimated as the transmission line L0910, with a truth degree value 0.855. Based on both the SCADA data in Table I and relay data in Table II, the only candidate for the fault section is estimated as the transmission line L0910, with truth degree value 0.882.

Case 2: A permanent fault occurred on the bus B04 at 0.05 second. A second permanent fault occurred on the bus B09 at 0.09 second. All the protection devices operated correctly. No false data occur. The observed SCADA data are listed in Table III. The observed relay data are listed in Table IV.

Based on the SCADA data in Table III, the candidates for the fault section are estimated and results are listed in Table V. Based on both the SCADA data in Table III and relay data in Table IV, the candidates for the fault section are estimated and the results are listed in Table VI.

Case 3: A permanent fault occurred on the transmission line L1314 at 0.05 second. A second permanent fault occurred on the bus B13 at 0.11 second. The circuit breakers CB1312 and CB1306 failed to open. The BR13 TRIP signal should be observed but it was not observed. The observed SCADA data are listed in Table VII. The observed relay data are listed in Table VIII.

Based on the SCADA data in Table VII, the candidates for the fault section are estimated and results are listed in Table IX. Based on both the SCADA data in Table VII and relay data in Table VIII, the candidates of the fault sections are estimated and the results are listed in Table X.

TABLE I
SCADA DATA OF CASE 1

Sequence No.	Time Stamp (Sec)	Observed Signal
1	0.1000	MLR0910 TRIP
2	0.1000	MLR1009 TRIP
3	0.2000	CB0910 OPEN
4	0.2000	CB1009 OPEN

TABLE II
RELAY DATA OF CASE 1

Sequence No.	Time Stamp (Sec)	Observed Signal
1	0.0662	SLR0409 PKP
2	0.0677	SLR0709 PKP
3	0.0693	BLR0910 PKP
4	0.0698	MLR0910 PKP
5	0.0703	MLR1009 PKP
6	0.0703	BLR1009 PKP
7	0.0703	SLR1110 PKP
8	0.0724	SLR1409 PKP
9	0.0740	MLR0910 OP
10	0.0745	MLR1009 OP

TABLE III
SCADA DATA OF CASE 2

Sequence No.	Time Stamp (Sec)	Observed Signal
1	0.1000	BR04 TRIP
2	0.2000	CB0402 OPEN
3	0.2000	CB0403 OPEN
4	0.2000	CB0405 OPEN
5	0.2000	CB0407 OPEN
6	0.2000	CB0409 OPEN
7	0.2000	BR09 TRIP
8	0.2000	CB0904 OPEN
9	0.2000	CB0907 OPEN
10	0.2000	CB0910 OPEN
11	0.2000	CB0914 OPEN

TABLE IV
RELAY DATA OF CASE 2

Sequence No.	Time Stamp (Sec)	Observed Signal
1	0.0537	BR04 PKP
2	0.0625	SLR0304 PKP
3	0.0651	SLR0904 PKP
4	0.0667	SLR0204 PKP
5	0.0667	SLR0504 PKP
6	0.0677	SLR0704 PKP
7	0.0703	BLR0704 PKP
8	0.0703	BLR0904 PKP
9	0.0766	BLR0204 PKP
10	0.0766	BLR0504 PKP
11	0.0771	BLR0304 PKP
12	0.0938	BR09 PKP
13	0.0964	SLR0709 PKP
14	0.1000	BR04 OP
15	0.1063	BLR0709 PKP
16	0.1115	SLR1009 PKP
17	0.1115	SLR1409 PKP
18	0.1115	SLR0409 PKP
19	0.1224	BLR1009 PKP
20	0.1224	BLR1409 PKP
21	0.1224	BLR0409 PKP
22	0.1401	BR09 OP

TABLE V
CANDIDATES FOR ESTIMATED FAULT SECTIONS BASED ON SCADA DATA OF CASE 2

Candidate No.	Fault Section	Truth Degree Value
1	B04	0.855
2	B09	0.855
3	L0409	0.513

TABLE VI
CANDIDATES FOR ESTIMATED FAULT SECTIONS BASED ON SCADA DATA AND RELAY DATA OF CASE 2

Candidate No.	Fault Section	Truth Degree Value
1	B04	0.882
2	B09	0.882
3	L0409	0.618

TABLE VII
SCADA DATA OF CASE 3

Sequence No.	Time Stamp (Sec)	Observed Signal
1	0.1000	MLR1314 TRIP
2	0.1000	MLR1413 TRIP
3	0.2000	CB1314 OPEN
4	0.2000	CB1413 OPEN
5	0.3000	BLR0613 TRIP
6	0.3000	BLR1213 TRIP
7	0.3000	CB0613 OPEN
8	0.3000	CB1213 OPEN

TABLE VIII
RELAY DATA OF CASE 3

Sequence No.	Time Stamp (Sec)	Observed Signal
1	0.0641	SLR1314 PKP
2	0.0651	SLR1413 PKP
3	0.0683	BLR1314 PKP
4	0.0688	BLR1413 PKP
5	0.0693	SLR0914 PKP
6	0.0698	MLR1314 PKP
7	0.0698	MLR1413 PKP
8	0.0703	SLR0613 PKP
9	0.0703	SLR1213 PKP
10	0.0740	MLR1314 OP
11	0.0740	MLR1413 OP
12	0.1141	BR13 PKP
13	0.1193	SLR0613 PKP
14	0.1204	SLR1213 PKP
15	0.1271	BLR0613 PKP
16	0.1297	BLR1213 PKP
17	0.1605	BR13 OP
18	0.2433	BLR0613 OP
19	0.2459	BLR1213 OP

TABLE IX
CANDIDATES FOR ESTIMATED FAULT SECTIONS BASED ON SCADA DATA OF CASE 3

Candidate No.	Fault Section	Truth Degree Value
1	L1314	0.855
2	B13	0.729
3	L1213	0.647
4	L0613	0.647

TABLE X
CANDIDATES FOR ESTIMATED FAULT SECTIONS BASED ON SCADA DATA AND RELAY DATA OF CASE 3

Candidate No.	Fault Section	Truth Degree Value
1	L1314	0.882
2	B13	0.854
3	L1213	0.722
4	L0613	0.722

B. Discussion

As shown in Case 1, if the scenario is a single fault without protection device failure and false data, the faulted section can be accurately identified. The truth degree value of the result based on both the relay data and SCADA data are higher than that based on only the SCADA data, because the relay data are assigned higher truth degree values due to their higher reliability. Case 2 is more complex than Case 1, because multiple faults occur. As shown in Table V and Table VI, besides the bus B04 and the bus B09, on which faults actually occur, the transmission line L0409, which has no fault, is included in the candidate set. The transmission line L0409 has a far smaller truth degree value than the other two candidates, which indicates small possibility of fault occurrence. Similar to Case 1, the truth degree values of the candidates based on both the relay data and SCADA data are higher than those based on only the SCADA data. Case 3 has additional complexity, because not only multiple faults but also protection device failure and false data are involved. As shown in Table IX and Table X, besides the transmission line L1314 and bus B13, on which fault actually occur, the transmission line L1213 and transmission line L0613, which have no fault, are included in the candidate set. The use of relay data increases the truth degree values for all candidates. It should be noticed that although the truth degree values of L1213 and L0613 are increased to some extent, the truth degree value of B13 are largely increased. The actual faulted sections can still be identified.

V. PROPOSED IMPLEMENTATION SOLUTION

The fault section estimation application will be implemented in a control center to assist the system operator in rapidly identifying faulted sections for restoration process. The structure of the application as well as its SCADA support infrastructure are illustrated in Fig. 11.

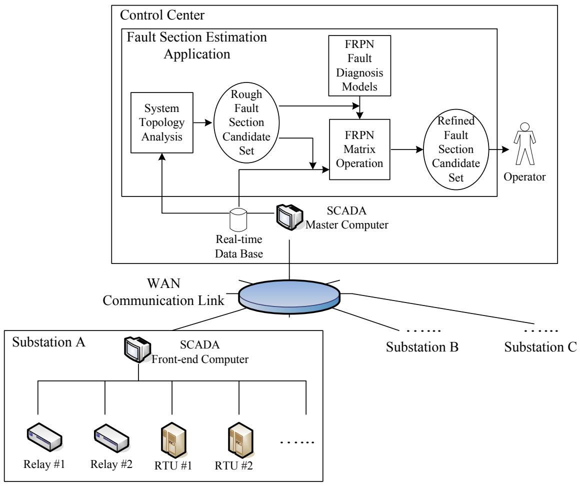

Fig. 11. Implementation of fault section estimation application

In such a solution, input data such as relay trip signals and circuit breaker status signals are acquired by RTUs of the SCADA system. Relay logic operand signals are defined in their data memories and retrieved from relays by the SCADA front-end computers in substations. The data are acquired from different substations and are transmitted to the control center through selected communication link such as microwave or optical fiber. In the control center, the SCADA master computer puts the input data into a real-time data base and keeps updating them at each scan time.

The fault section estimation application includes two stage analysis. In the first stage, the system topology is analyzed based on circuit breaker status data in the real-time data base. The analysis will include all sections isolated by the opening of circuit breakers into a rough candidate set. The set is rough because it more likely includes sections which are not faulted but are isolated due to backup relay operation. In the second stage analysis, the Fuzzy Reasoning Petri-net diagnosis model as well as data in the real-time data base corresponding to each section in the rough candidate set are used and Fuzzy Reasoning Petri-net matrix operation is implemented. As a result, each section will be associated with a truth degree value. The section with a truth degree value greater than a certain threshold will be included in the refined candidate set. Such a refined candidate set is presented to the system operator for decision-making.

In such a solution, the FRPN models which are represented by all kind of matrices are separated from FRPN matrix operations. This is analogous to an expert system whose rule-base is separated from its inference engine. The FRPN models can be built in advance based on power system and protection system configurations and stored in files. In such a way, the FRPN models can be easily modified according to the changes of input data as well as power system and protection system configuration.

VI. Conclusion

FRPN technique possesses the strength of Expert System and Fuzzy Logic as well as parallel information processing, which is quite suitable to tackle the problem of power system fault section estimation. This paper discusses solutions aiming to gain full advantages of FRPN, as an approach to fault section estimation. The optimal design of structure of FRPN diagnosis models is proposed to avoid large matrix size and achieve better estimation performance. Several fuzzy logic parameters are associated with particular probability concepts in protection systems to effectively handle uncertainties. An matrix reasoning execution algorithm is introduced to realize parallel processing capability. The separation of matrix model data and matrix reasoning operation, which is analogous to the separation of rule base and inference engine in an expert system, is conceptualized to facilitate update of models. Integration of logic operand data of digital protective relays as additional inputs with conventional SCADA data is proposed to enhance estimation accuracy. As a result, the proposed FRPN based fault section estimation implementation is faster, more accurate and more adaptive to the change of system configuration.

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