An Analytic Model for Fault Diagnosis in Power Systems Considering Malfunctions of Protective Relays and Circuit Breakers

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An Analytic Model for Fault Diagnosis in Power Systems Considering Malfunctions of Protective Relays and Circuit Breakers

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***Abstract*—When a fault occurs on a section or a component in a given power system, if one or more protective relays (PRs) and/or circuit breakers (CBs) associated do not work properly, or in other words, a malfunction or malfunctions happen with these PRs and/or CBs, the outage area could be extended. As a result, the complexity of the fault diagnosis could be greatly increased. The existing analytic models for power system fault diagnosis do not systematically address the possible malfunctions of PRs and/or CBs, and hence may lead to incorrect diagnosis results if such malfunctions do occur. Given this background, based on the existing analytic models, an effort is made to develop a new analytic model to well take into account of the possible malfunctions of PRs and/or CBs, and further to improve the accuracy of fault diagnosis results. The developed model does not only estimate the faulted section(s), but also identify the malfunctioned PRs and/or CBs as well as the missing and/or false alarms. A software system is developed for practical applications, and realistic fault scenarios from an actual power system are served for demonstrating the correctness of the presented model and the efficiency of the developed software system.**

***Index Terms*—Alarm message, analytic model, fault diagnosis, malfunctions of protective relays and circuit breakers, power system.**

I. Introduction

WHEN a fault occurs on a section in a power system, the corresponding protective relays (PRs) should operate to trip related circuit breakers (CBs) off, so as to isolate the fault section from the healthy part of the power system. If a malfunction or malfunctions are happening with these PRs and/or CBs, the outage area could be significantly extended. Under complicated fault situations, a flood of alarm information could be displayed on the console in the control center, and lead to the difficulty for dispatchers to identify the faulted section in a short time. Thus, precise and effective method for power system fault diagnosis plays an important role in supporting network restoration for dispatchers.

Up to now, the most established approaches, which have been put into or of potential for practical applications, can be grouped into three categories: the expert system-based [1]–[6], artificial neural network-based [7]–[10], and the analytic model-based methods [11]–[17]. In addition, other artificial intelligent methods such as the rough set (RS) [18], Petri net [19], [20], and Bayesian networks [21] have also been proposed for power system fault diagnosis in recent years with preliminary research results reported.

Since a great deal of expertise and the logic based reasoning are needed to cope with fault diagnosis problems, expert systems (ES) have been extensively used in on-line fault diagnosis of power systems. Take two practical applications for instance: 1) a Generalized Alarm Analysis Module (GAAM) employing the techniques presented in [1] was integrated into the EMS (Energy Management System) environment at control centers in Italy; 2) A fault diagnosis ES for distribution substations presented in [2] has been installed in a local control center in Korea as a part of an intelligent guidance system for the SCADA operators. In [3] the problem of fault section estimation is dealt with by combining artificial neural network (ANN) and ES techniques: ANNs are employed to model the protection systems with particular emphasis on handling the uncertainties involved with PR operation and CB tripping messages; An expert system is then used to complement the results provided by the ANNs with the network topology considered. In [1]–[6], ES based approaches were proposed for fault section estimation with malfunctions of PRs and CBs taken into account. These approaches could work well if all received alarms are correct. However, once there are incorrect or missing alarms, false diagnosis results may be obtained.

ANN is an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase. It can be used to model complex relationships between inputs and outputs or to find patterns in data. The advantage of ANN based methods lies in that no explicit rules are required to precisely define the power system

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configuration and PR scheme [7]–[10]. In [7], the protection systems of buses, transmission lines, and transformers are modeled using two types of neural networks: the general regression neural network (GRNN) and the multilayer perceptron neural network (MPNN). In [8], the application of radial basis function (RBF) neural networks for fault classification and location in transmission lines is presented. Using measurements available at the substation, as well as the PR and CB status, an ANN and support vector machine (SVM) approach is proposed for locating faults in radial distribution systems in [9].

The analytic model-based methods for power system fault diagnosis were developed in [11]–[17]. A key issue in this kind of methods is to build up a criterion that could well reflect the discrepancy between the actual and the expected states of PRs and CBs. Then an optimization method, such as the Genetic Algorithm (GA) [11], [12], Tabu Search (TS) [13], [14], Particle Swarm Optimization (PSO) [15], and Evolution Algorithm (EA) [16], can be employed to search for a fault hypothesis (FH) or hypotheses (FHs) which minimize the criterion, i.e., to find the most likely FH(s) that could well explain the received alarm messages. In the analytic model-based methods, the power system fault diagnosis is formulated as an unconstrained 0–1 integer programming problem, and as a result this kind of methods could deal with complicated fault scenarios, especially the ones with incorrect or missing alarms.

In the existing analytic models for the power system fault diagnosis, a FH only involves the information about "the actual states of section(s) in the outage area (healthy or faulted)". In determining the expected states of PRs and CBs, their possible malfunctions are not taken into account and this may lead to false diagnosis results if one or more malfunctions of some PRs and/or CBs associated do occur.

Based on the work presented in [11]–[17], an analytic model is developed for power system fault diagnosis with malfunctions of PRs and CBs taken into account, and the problem is then formulated as an integer programming problem and solved by the well developed TS method. The main contributions of this paper include the following three aspects.

1) A new form of the FH is presented, including the information about "the actual states of section(s) in the outage area (healthy or faulted)", as well as "the actual operating states of PRs and CBs (normal or malfunctioned)".
2) A novel criterion is presented (i.e., the objective function of the optimization problem) with malfunctions of PRs and CBs taken into account. Here, the key issue is to determine the expected states of PRs and CBs corresponding to a given FH. The fault diagnosis model to be developed could not only estimate fault section(s), but also identify the malfunctioned PRs and CBs, as well as the incorrect and missing alarms.
3) Based on the developed fault diagnosis model, a software system is designed and implemented to meet the requirements of actual power systems. The developed software package has been employed by Guangdong Power Dispatching Center in south China. Actual fault scenarios are employed to demonstrate the feasibility and efficiency of the developed model and approach.

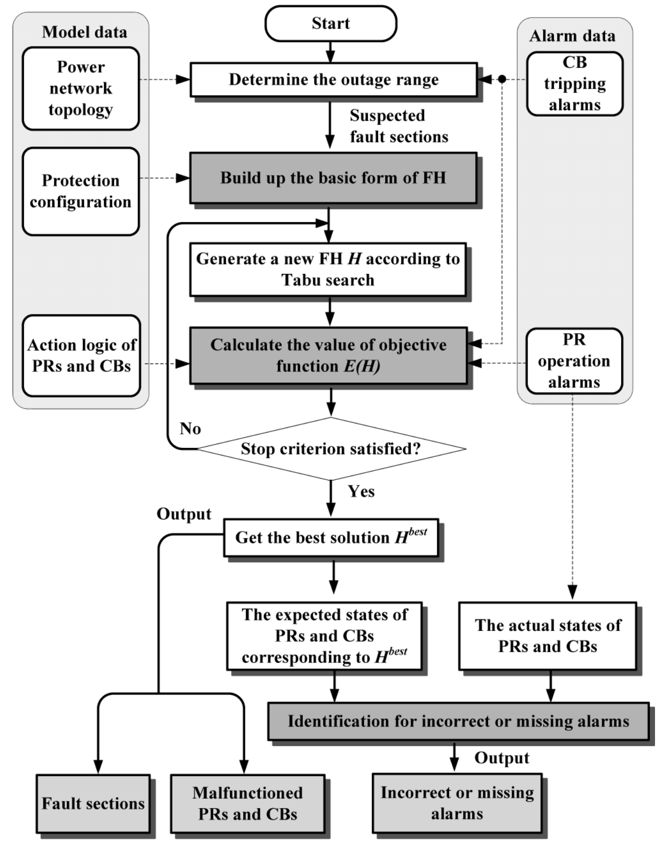


Fig. 1. Framework of the developed fault diagnosis method.

II. The Framework of the Developed Analytic Model-Based Approach

The framework of the developed analytic model-based approach for power system fault diagnosis is shown in Fig. 1. First, the outage area is identified to obtain the suspected fault sections using a real-time network topology determination method [22], so as to reduce the scale of the optimization problem to be formulated in the next step. Three key modules, namely "Build up the basic form of a FH", "Calculate the value of the objective function $E(H)$", and "Identify incorrect or missing alarms", are presented in Section III, Section IV, and Section V, respectively.

The diagnosis results include the following three types:
1) fault sections;
2) malfunctioned PRs and CBs;
3) the incorrect and missing alarms.

III. The Fault Hypothesis

For the convenience of presentation, several sets are defined first as follows:
1) $\{d_1, d_2, \ldots, d_{n_d}\}$ is the set of sections located in the outage area, and d_i is the ith section in this set;
2) $\{r_1, r_2, \ldots, r_{n_r}\}$ is the set of PRs which are configured for $d_1, d_2, \ldots, d_{n_d}$, and r_i is the ith PR in this set;
3) $\{c_1, c_2, \ldots, c_{n_c}\}$ is the set of CBs which are connected to $d_1, d_2, \ldots, d_{n_d}$ before a fault occurs, and c_i is the ith CB in this set.

A fault hypothesis (FH) is used to represent "what happened to trigger the received alarms". If a FH is consistent with actual fault situation, then the FH is deemed true. The defined FH here not only involves the information about "the states of section(s) in the outage area (healthy or faulted)", as well as "the operating states of PRs and CBs (normal or malfunctioned)".

Malfunctions of PRs and CBs can be classified into four types:

1) a PR fails to operate;
2) a PR operates incorrectly;
3) a tripping signal is sent from a PR, but the CB associated fails to be tripped off;
4) no tripping signal is sent from a PR, but the CB associated is tripped off (i.e., the CB is tripped incorrectly).

With malfunctions of PRs and CBs taken into account, a FH is defined mathematically as follows:

$$H = [D, F, M] \tag{1}$$

where

D $[d_1, d_2, \ldots, d_{n_d}]$, and d_k represents the state of the kth section in the outage area, with $d_k = 0$ and 1, respectively, corresponding to its normal and faulted state;

F $[f_{r_1}, f_{r_2}, \ldots, f_{r_{n_r}}, f_{c_1}, f_{c_2}, \ldots, f_{c_{n_c}}]$. If r_i operates incorrectly, then $f_{r_i} = 1$, otherwise $f_{r_i} = 0$. Similarly, if c_j is tripped off incorrectly, then $f_{c_j} = 1$, otherwise $f_{c_j} = 0$;

M $[m_{r_1}, m_{r_2}, \ldots, m_{r_{n_r}}, m_{c_1}, m_{c_2}, \ldots, m_{c_{n_c}}]$. If r_i fails to operate, then $m_{r_i} = 1$, otherwise $m_{r_i} = 0$. Similarly, if c_j fails to be tripped off, then $m_{c_j} = 1$, otherwise. $m_{c_j} = 0$.

IV. The Objective Function

A. The Basic Form of the Objective Function

The objective function $E(H)$ reflects the credibility of H defined in (1). A smaller $E(H)$ suggests a higher credibility of H. Thus, the power system fault diagnosis problem could be formulated as an optimization problem, with the objective of finding a FH (or FHs) that minimizes $E(H)$.

$E(H)$ is determined by the following procedure:

1) if H is an unreasonable FH, H must not be a correct solution of the fault diagnosis problem. Thus, once H is an unreasonable FH, $E(H)$ should be assigned a large value such as $E(H) = 100000$, so that an unreasonable FH will, in any case, not be the optimal solution of the fault diagnosis problem;
2) if H is a reasonable FH, $E(H)$ is determined as follows:

$$\begin{aligned} E(H) &= w_1\left(\sum_i^{n_r}|\Delta r_i(H)| + \sum_j^{n_c}|\Delta c_j(H)|\right) + w_2|H| \\ &= w_1\left(\sum_i^{n_r}|r_i - r_i^*(H)| + \sum_j^{n_c}\left|c_j - c_j^*(H)\right|\right) \\ &\quad + w_2\left(\sum_k^{n_d}|d_k| + \sum_i^{n_r}(|f_{ri}| + |m_{ri}|) \right.\\ &\qquad \left. + \sum_j^{n_c}(|f_{cj}| + |m_{cj}|)\right). \end{aligned} \tag{2}$$

Equation (2) consists of the following two parts:

1) The Discrepancy Index: $\sum_i^{n_r}|\Delta r_i(H)| + \sum_j^{n_c}|\Delta c_j(H)|$.

This index reflects the discrepancy between the expected and actual states of PRs and CBs, i.e., $|\Delta r_i(H)| = |r_i - r_i^*(H)|$ and $|\Delta c_j(H)| = \left|c_j - c_j^*(H)\right|$.

Here, r_i represents the actual state of the ith PR, and $r_i = 0$ or 1 corresponds to the nonoperational or operational state; c_j represents the actual state of the jth CB, and $c_j = 0$ and 1 corresponds to the tripped (open) or non-tripped (closed) state; $r_i^*(H)$ represents the expected state of the ith PR corresponding to H. If the ith PR should not operate, $r_i^*(H) = 0$, otherwise $r_i^*(H) = 1$; $c_j^*(H)$ represents the expected state of the jth CB. If the jth CB should not be tripped off. $c_j^*(H) = 0$, otherwise $c_j^*(H) = 1$.

2) The Minimum Index: $|H|$

The contribution of this part is that: if the total number of the fault sections as well as the malfunctioned PRs and CBs, i.e., $\left(\sum_k^{n_d}|d_k| + \sum_i^{n_r}(|f_{ri}| + |m_{ri}|) + \sum_j^{n_c}(|f_{cj}| + |m_{cj}|)\right)$ is large, the probability of H to be the optimal solution will be low.

Here, w_1 and w_2 are the weights of the discrepancy index and minimum index, respectively, and $w_1 >> w_2$. In this work, it is specified that $w_1 = 100$ and $w_2 = 1$. $w_1 >> w_2$ means that the discrepancy index is much more important than the minimum index. The specified large weight of the discrepancy index is used to guarantee that FHs which are able to well explain the received alarms can be found. Then, after taking the discrepancy index into account, the purpose of imposing the minimum index is to select the FH which includes the smallest number of fault sections, malfunctioned PRs and CBs, because the probability of multiple faults and multiple malfunctions of PRs and CBs is smaller than that of a single event (fault or malfunction).

The procedure of determining $E(H)$ is shown in Fig. 2. In this figure, $a_{ri}(H)$ and $a_{cj}(H)$ represent the expected states of r_i and c_j, respectively. If PRs and CBs work properly, $a_{ri}(H)$ and $a_{cj}(H)$ could be determined directly according to the operating logics of PRs and CBs. $r_i^*(H)$ and $c_j^*(H)$ represent the expected states of r_i and c_j, respectively, with malfunctions of PRs and CBs taken into account.

B. Determination of $a_ri(H)$ and $a_cj(H)$

1) The Determination of $a_ri(H)$: First, some symbols are defined below:

1) $\otimes$ and $\oplus$ represent logic multiplication and summation, respectively;
2) $Z(r_i)$ is the set of sections in the protection zone of r_i;
3) $R(c_j)$ is the set of PRs which trip c_j off;
4) $p_{a,cj}, p_{b,cj}$ and $p_{c,cj}$ represent that the tripping phase of c_j is phase A, B, and C, respectively.

Several kinds of PRs are discussed below.

1) *Main Protection (MP)*

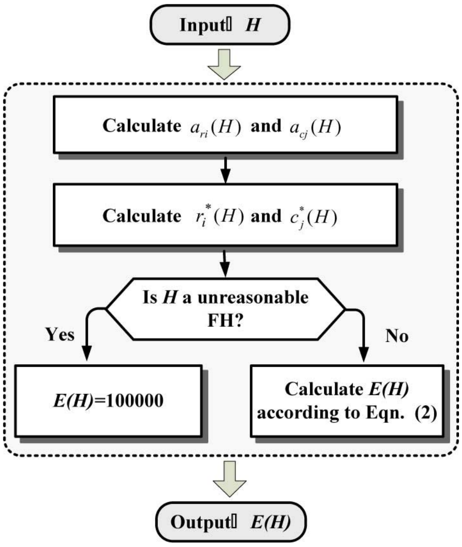
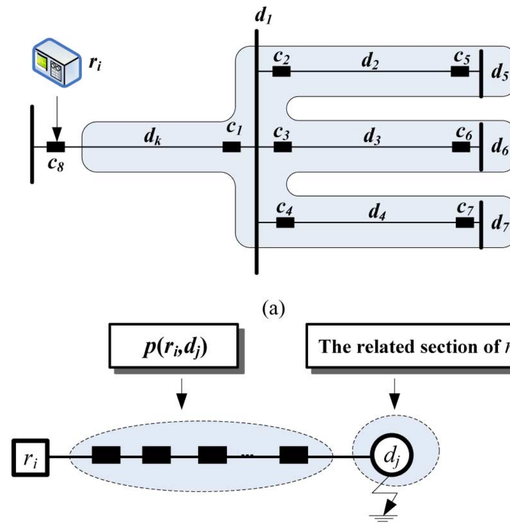


Fig. 2. Procedure of determining $E(H)$.



(b)

Fig. 3. (a) Determination of the related section according to the protection zone of r_i. (b) Related path from r_i to d_k.

Suppose that r_i is the MP of d_k. The operating logic of r_i is: if a fault occurs on d_k, r_i should operate, i.e.,

$$a_{ri}(H) = d_k. \tag{3}$$

2) *Primary Backup Protection (PBP)*
Suppose that r_i and r_x are the PBP and MP of d_k, respectively. The operating logic of r_i is: if a fault occurs on d_k, and r_x fails to operate (i.e., $m_{rx} = 1$), then should operate, i.e.,

$$a_{ri}(H) = d_k \otimes m_{rx}. \tag{4}$$

3) *Secondary Backup Protection (SBP)*
Suppose that r_i, r_x and r_y are the SBP, MP, and PBP of d_k, respectively. The operating logic of r_i is as follows.

a) If a fault occurs on d_k, and both r_x and r_y fail to operate (i.e., $m_{rx} = 1$ and $m_{ry} = 1$), then r_i should operate, i.e.,

$$a_{ri}(H) = d_k \otimes m_{rx} \otimes m_{ry}. \tag{5}$$

b) First, the concepts of the related section and related path are defined. As shown in Fig. 3(a), the related sections of r_i are the sections in the protection zone of r_i but excluding the local section d_k. For the example shown in Fig. 3(a) $Z(r_i) = \{d_1, d_2, d_3, d_4, d_5, d_6, d_7\} \cdot p(r_i, d_j)$, the related path from r_i to d_k, represents the acyclic electrical path from the location of r_i to its related section d_k. It is defined that $p(r_i, d_j) = \{c_{\tau 1}, c_{\tau 2}, \ldots, c_{\tau n}\}$, and here $c_{\tau 1}, c_{\tau 2}, \ldots, c_{\tau n}$ are the sequence of the CBs along the path. For the example shown in Fig. 3(a), $p(r_i, d_5) = \{c_1, c_2, c_5\}$. As shown in Fig. 3(b), r_i protects its related section $d_j \in Z(r_i)(p(r_i, d_j))$ through $p(r_i, d_j)$. If a fault occurs on d_j, and all CBs along $p(r_i, d_j)$ are closed (i.e., $\prod_{c_p \in p(r_i,d_j)} \overline{c_p} = 1$), this means that the fault has not yet been cleared. In this case, r_i should operate, i.e.,

$$a_{ri}(H) = \sum_{d_j \in Z(r_i)} \left(d_j \otimes \prod_{c_p \in p(r_i,d_j)} \overline{c_p} \right). \tag{6}$$

Then, $a_{ri}(H)$ can be determined as

$$a_{ri}(H) = d_k \otimes m_{rx} \otimes m_{ry} \oplus \sum_{d_j \in Z(r_i)} \left(d_j \otimes \prod_{c_p \in p(r_i,d_j)} \overline{c_p} \right). \tag{7}$$

4) *Breaker Failure Protection (BFP)*
Suppose that c_j is connected to d_k, and r_i is the BFP of c_j. The operating logic of r_i is: if any tripping signal is received from $r_x \in R(c_j)$, but c_j fails to be tripped off, then should operate, i.e.,

$$a_{ri}(H) = \left(\sum_{r_x \in R(c_j)} r_x \right) \otimes m_{cj}. \tag{8}$$

5) *Automatic Recloser (AR)*
There are several types of ARs. Only the single-phase AR is considered as an instance in this work. Suppose that r_i is the AR of d_k, and c_j is the reclosing CB corresponding to r_i. The operating logic of r_i is: if $r_x \in R(c_j)$ operates and c_j is tripped off with a single phase, then r_i should operate to reclose c_j, i.e.,

$$a_{ri}(H) = \left(\sum_{r_x \in R(c_j)} r_x \right) \otimes c_j \otimes (p_{a,cj} \otimes \overline{p_{b,cj}} \otimes \overline{p_{c,cj}} \oplus \overline{p_{a,cj}} \otimes p_{b,cj} \otimes \overline{p_{c,cj}} \oplus \overline{p_{a,cj}} \otimes \overline{p_{b,cj}} \otimes p_{c,cj}). \tag{9}$$

TABLE I
DETERMINATION OF $r_i^*(H)$ AND $c_j^*(H)$

m_{ri} (m_{cj})	f_{ri} (f_{cj})	$a_{ri}(H)$ ($a_{cj}(H)$)	$r_i^*(H)$ ($c_j^*(H)$)	Notes
1	0	1	0	According to the operating logic, r_i should operate. However, r_i failed to operate so that the operating alarm of r_i could not be received. (According to the operating logic, c_j should be tripped off. However, c_j failed to trip so that the tripping alarm of c_j could not be received.)
0	1	0	1	According to the operating logic, r_i should not operate. However, r_i operated incorrectly so that the operating alarm of r_i was received. (According to the operating logic, c_j should not be tripped off. However, c_j tripped incorrectly so that the tripping alarm of c_j was received.)
0	0	1	1	According to the operating logic, r_i should operate. r_i is working properly so that it will operate and the operating alarm of r_i will be received. (According to the operating logic, c_j should be tripped off. c_j is working properly so that it will be tripped off and the tripping alarm of c_j will be received.)
0	0	0	0	According to the operating logic, r_i should not operate. r_i is working properly so that r_i will not operate and the operating alarm of r_i will not be received. (According to the operating logic, c_j should be tripped off. c_j is working properly so that the tripping alarm of c_j will not be received.)
1	1	1	-	This is an unreasonable fault hypothesis because m_{ri} =1 and f_{ri} =1 are contradictory. (This is an unreasonable fault hypothesis because m_{cj} =1 and f_{cj} =1 are contradictory.)
1	1	0	-	This is an unreasonable fault hypothesis because m_{ri} =1 and f_{ri} =1 are contradictory. (This is an unreasonable fault hypothesis because m_{cj} =1 and f_{cj} =1 are contradictory.)
1	0	0	-	This is an unreasonable fault hypothesis because $a_{ri}(H)$ =0 and m_{ri} =1 are contradictory. (This is an unreasonable fault hypothesis because $a_{cj}(H)$ =1 and m_{cj} =1 are contradictory.)
0	1	1	-	This is an unreasonable fault hypothesis because $a_{ri}(H)$ =1 and f_{ri} =1 are contradictory. (This is an unreasonable fault hypothesis because $a_{cj}(H)$ =1 and f_{cj} =1 are contradictory.)

Note: The determination of $c_j^*(H)$ is shown in the bracket

2) Determination of $a_cj(H)$*:* The operating logic of CBs is: if tripping signals are received from $r_x \in R(c_j)$, then should be tripped off, i.e.,

$$a_{cj}(H) = \sum_{r_x \in R(c_j)} r_x^*(H).$$

C. Determination of and $r_i^*(H)$ *and* $c_j^*(H)$

As shown in Table I, based on $a_{ri}(H)$ and $a_{cj}(H)$ obtained in accordance with (3)–(9), $r_i^*(H)$ and $c_j^*(H)$ can be determined as follows:

$$\begin{aligned} r_i^*(H) =& \overline{m_{ri}} \otimes \overline{f_{ri}} \otimes a_{ri}(H) \oplus \overline{m_{ri}} \otimes f_{ri} \otimes \overline{a_{ri}(H)} \\ c_j^* =& \overline{m_{cj}} \otimes \overline{f_{cj}} \otimes a_{cj}(H) \oplus \overline{m_{cj}} \otimes f_{cj} \otimes \overline{a_{cj}(H)}. \end{aligned}$$

Moreover, as shown in Table I, unreasonable FHs can be grouped into three types.

1) "$m_{ri} = f_{ri} = 1$", or $m_{cj} = f_{cj} = 1$".

2) "$a_{ri} = 0$ and $m_{ri} = 1$", or "$a_{cj}(H) = 0$ and $m_{cj} = 1$"; "$a_{ri} = 1$ and $f_{ri} = 1$", or "$a_{cj}(H) = 1$ and "$f_{cj} = 1$.

V. IDENTIFICATION OF INCORRECT OR MISSING ALARMS

The well-established TS [23], [24] could be applied to solve the unconstrained 0–1 integer programming problem formulated in Section IV to obtain the optimal solution H^{best}. Then, the identification of incorrect or missing alarms could be carried out by employing the method shown in Table II. In this table, it is supposed that the optimal solution is unique. If multiple optimal solutions exist, a similar way is applicable).

VI. SOFTWARE DESIGN AND IMPLEMENTATION

As shown in Fig. 4, based on the developed method, a software package is developed for actual applications in utility companies. Two data sources are included.

1) The IEC 61970 [25] based Energy Management System (EMS) provides an integrated solution through defining a

TABLE II
IDENTIFICATION OF INCORRECT OR MISSING ALARMS

Expected States	Actual States	The identification of incorrect or missing alarms
$r_i^*(H^{best})=1$	$r_i=0$	The operating alarm of r_i is missing
$r_i^*(H^{best})=0$	$r_i=1$	The operating alarm of r_i is incorrect
$c_j^*(H^{best})=1$	$c_j=0$	The tripping alarm of c_j is missing
$c_j^*(H^{best})=0$	$c_j=1$	The tripping alarm of c_j is incorrect alarm

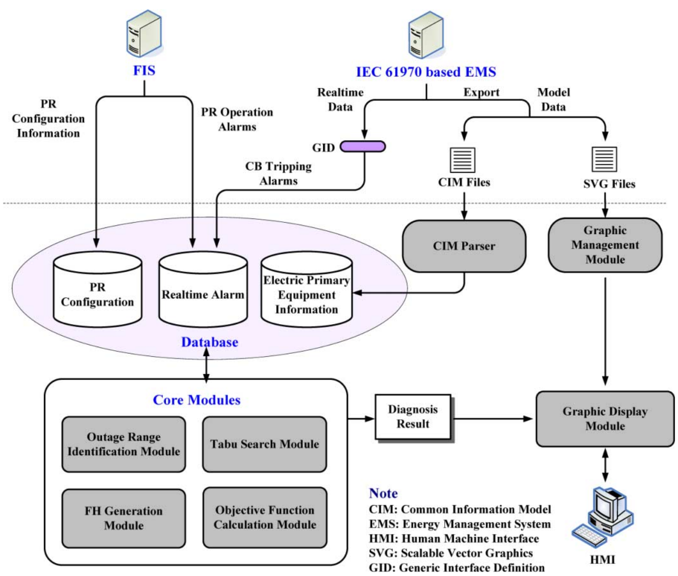


Fig. 4. Framework of the developed software system.

Common Information Model (CIM) for electric primary equipments and standardizing a Generic Interface Definition (GID), which provides access to SCADA systems for obtaining CB tripping alarms. The single-line diagrams of the power network concerned and each substation are exported from the IEC 61970 based EMS, with a standard graphic format, namely Scalable Vector Graphics (SVG).

2) The Fault Information System (FIS) provides the PR configuration information and the real time PR operating alarms.

The software system is implemented by employing C# under the platform of Visual Studio 2005. It is now employed by Guangdong Power Dispatching Center, China.

VII. APPLICATION EXAMPLES

The power system in Guangdong Province, China, is composed of 25 substations, 57 transformers, and 73 transmission lines with a voltage level of 500 kV, and 511 substations, 511 transformers and 594 transmission lines with voltage level of 220 kV. Many actual fault scenarios from the Guangdong Power

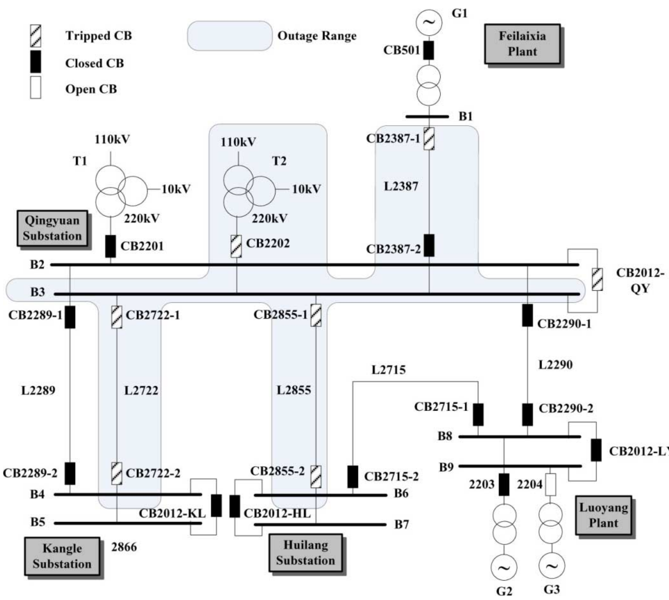


Fig. 5. Power system diagram associated with the fault scenarios 1.

TABLE III
ENCODING OF SUSPECTED FAULT SECTIONS, RELATED CBS AND PRS

Suspected Fault Sections in the Outage Area			
L2387	d_1	B2	d_4
L2722	d_2	B3	d_5
L2855	d_3	T2	d_6
Related CBs			
CB2387-1	c_1	CB2855-1	c_5
CB2387-2	c_2	CB2855-2	c_6
CB2012-QY	c_3	CB2722-1	c_7
CB2202	c_4	CB2722-2	c_8
Related PRs			
MPs of L2387, L2722 and L2855 (Qingyuan)			r_1~r_3
PBPs of L2387, L2722 and L2855 (Qingyuan)			r_4~r_6
SBPs of L2387, L2722 and L2855 (Qingyuan)			r_7~r_9
ARs of L2387, L2722 and L2855 (Qingyuan)			r_{10}~r_{12}
MP, PBP, SBP and AR of L2387 (Feilaixia)			r_{13}~r_{16}
MP, PBP, SBP and AR of L2722 (Kangle)			r_{17}~r_{20}
MP, PBP, SBP and AR of L2855 (Huilang)			r_{21}~r_{24}
BFPs of CB2387-1, CB2387-2, CB2012-QY, CB2202, CB2855-1. CB2855-2, CB2722-1, CB2722-2			r_{25}~r_{32}
MPs of B2 and B3			r_{33}, r_{34}
MP, PBP and SBP of T2			r_{35}~ r_{37}

System are used to test the developed on-line fault diagnosis software package, and the diagnosis results are correct except for one case with many missing alarms. The proposed approach may not work well for situations with many missing alarms, and the detailed analysis for the reason will be presented in part C in this section. Due to the space limitation, only two tested scenarios are presented in this section. To facilitate the understanding of the developed model and approach, the first fault scenario will be described in detail, and only the diagnosis result will be presented for the fault scenario 2.

A. The Fault Scenario 1

This actual fault scenario happened in Qingyuan Substation on May 2, 2006. The related power network and received alarms are shown in Fig. 5 and Table V, respectively.

The fault scenario is detailed as follows.

1) A fault occurred on L2387.
2) The MP of L2387 in Qingyuan Substation operated and then a signal was sent to trip off CB2387–2, but the phase A of CB2387–2 was burning and failed to be tripped off.
3) The BFP of CB2387–2 operated to successfully trip off CBs connected to B3, i.e., CB2722–1, CB2855–1, CB2202 and CB2012-QY.
4) Due to the tripping of CB2722–1 and CB2855–1 in Qingyuan Substation, the blocking signals of pilot systems cannot be transferred to the other terminals of L2722 and L2855. Thus, the pilot protections of L2722 and CB2855 operated to trip L2722–2 and CB2855–2 off, respectively.
5) Finally, the outage area is formed as shown in the shadow area in Fig. 5.

The fault diagnosis procedure by the proposed method is carried out as follows.

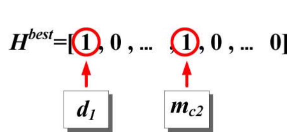
1) The first step of the proposed method is to determine the outage area, and the sections included in this area are the suspected fault sections. They are encoded in Table III.
2) The related PRs and CBs can be determined as listed in Table III. Then, the basic form of a FH is obtained as

$$H = [d_1, \dots d_6, f_{r_1}, \dots f_{r_{37}}, f_{c_1}, \dots, f_{c_8}, m_{r_1}, \dots m_{r_{37}}, m_{c_1}, \dots m_{c_8}].$$

3) Determine the basic form of the objective function $E(H)$ as stated in Part A, Section IV. The key issue lies in the determination of $r_i^*(H)$ and $c_j^*(H)$ according to the method proposed in Section IV. For better understanding the operation of the proposed fault diagnosis model, take the determination of $r_{14}^*(H)$ and $c_4^*(H)$ for instances

$$\begin{aligned} a_{r14}(H) &= (r_1 \oplus r_4 \oplus r_7) \otimes m_{c2} \\ r_{14}^*(H) &= \overline{m_{r14}} \otimes \overline{f_{r14}} \otimes a_{r14}(H) \oplus \overline{m_{r14}} \otimes f_{r14} \\ &\quad \otimes \overline{a_{r14}(H)} \\ a_{c4}(H) &= r_{14}^*(H) \otimes r_{34}^*(H) \otimes r_{35}^*(H) \otimes r_{36}^*(H) \\ &\quad \otimes r_{37}^*(H) \\ c_4^*(H) &= \overline{m_{c4}} \otimes \overline{f_{c4}} \otimes a_{c4}(H) \oplus \overline{m_{c4}} \otimes f_{c4} \otimes \overline{a_{c4}(H)}. \end{aligned}$$

4) According to the reported alarms, r_i and c_j, the actual states of PRs and CBs, can be obtained:$r_1, r_{13}, r_{17}, r_{20}, r_{21}, r_{24}, r_{26}, c_1, c_3, c_4, c_5$, and c_7, are all equal to 1; and other r_i and c_j equal to 0. By now, for a given FH, the value of $E(H)$ could be determined.
5) Using the TS method, the optimal solution of the optimization problem could be obtained as:



i.e., L2387 was the fault section ($d_1 = 1$) and CB2387-2 was failed to be tripped off ($m_{c2} = 1$).

TABLE IV
DIAGNOSIS RESULT REPORT

The Diagnosis Result Report	
Occurrence Time	11:06:02 May 2, 2006
Outage Area	L2387, L2722, L2855, B2, B3, T2
Fault Sections	L2387
Malfunction PRs	-
Malfunction CBs	Qingyuan Substation: CB2387-2 (Failed to be tripped off)
Missing Alarms	-
Incorrect Alarms	-

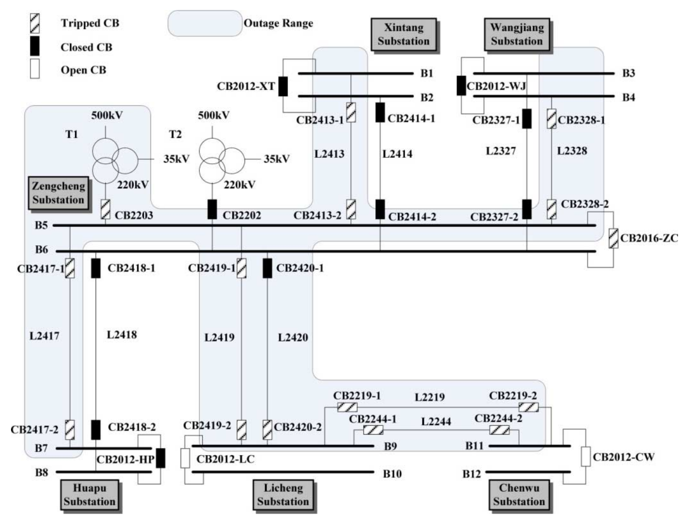


Fig. 6. Power system diagram associated with the fault scenario 2.

The diagnosis result report generated by the implemented software is shown in Table IV. They are consistent with those actually happened.

B. The Fault Scenario 2

This fault case happened in Zengcheng Substation in the Guangdong Power System in China on September 18, 2008. The related power network and received alarms are shown in Fig. 6 and Table VI, respectively.

The fault scenario is detailed as follows.

1) A fault occurred on the transmission line L2417.
2) The MP of L2417 in Zengcheng substation operated and then a signal was sent to trip off CB2417–1, but CB2417–1 failed to be tripped off.
3) The BFP of CB2417–1 operated to trip the CBs surrounding CB2417–1.
4) The BFP of CB2219–1 in Licheng substation operated incorrectly. As the result, the CBs surrounding CB2219–1 were tripped off.
5) Finally, as shown in Fig. 6, the outage area was formed.

The developed software package was used to test the fault case, and obtained diagnosis results are shown in Table VII.

The fault diagnosis results are consistent with those actually happened.

C. Performance Analysis

The computation time required for fault scenario 1 is 3380 ms, while for fault scenario 2 it is 4510 ms, on a PC with 2.1-GHz Dual-Core Processor (AMD Athlon 64 × 2 Dual) and

TABLE V
RECEIVED ALARMS

Substation/Plant	Received Alarms
Qingyuan	MP of L2387 operated; BFP of CB2387-2 operated; CB2722-1 tripped off; CB2855-1 tripped off; CB2202 tripped off; CB2012-QY tripped off.
Feilaixia	MP of L2387 operated; CB2387-1 tripped off.
Huilang	MP of L2855 operated; The phase A of CB2855-2 tripped off; The phase A of CB2855-2 reclosed successfully.
Kangle	MP of L 2722 operated; The phase A of CB2722 -2 tripped off; The phase A of CB2722 -2 reclosed successfully.

TABLE VI
RECEIVED ALARMS

Substation	Received Alarms
Zengcheng	MP of L2417 operated; BFP of CB2417-1 operated; CB2203 tripped off; CB2419-1 tripped off; CB2328-2 tripped off; CB2413-2 tripped off; CB2016-ZC tripped off.
Licheng	BFP of CB2219-1 operated; CB2419-2 tripped off; CB2420-2 tripped off; CB2219-1 tripped off; CB2244-1 tripped off.
Wangjiang	MP of L2328 operated; CB2328-1 tripped off.
Chenwu	MP of L2219 operated; MP of L2244 operated; CB2219-2 tripped off; CB2244-2 tripped off.
Huapu	MP of L2417 operated; CB2417-2 tripped off.
Xintang	MP of L2413 operated; CB2413-1 tripped off.

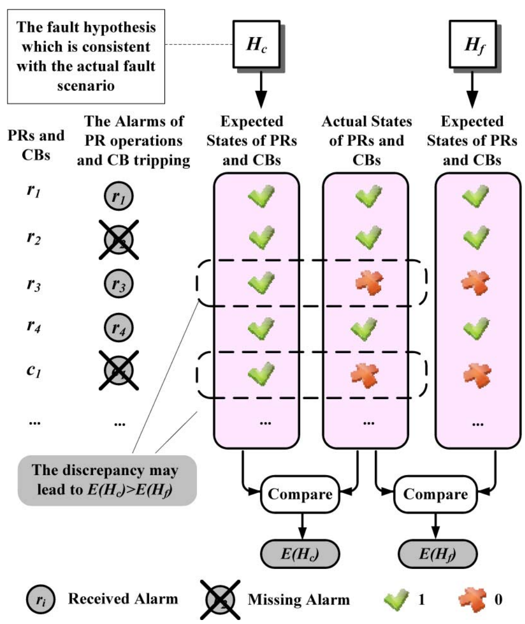


Fig. 7. Analysis of the diagnosis performance.

2-GB memory. The spent computation time is dependent on the number of sections, PRs, and CBs located in the outage area, since they are optimization variables to be found.

It is shown by test results that the developed model and method could lead to correct diagnosis results, even in the cases with malfunctioned PRs and CBs. However, for those fault scenarios with many missing alarms due to communication channel failures or others, false diagnosis results may be obtained. As shown in Fig. 7, due to the alarm missing, H_c, the FH which is consistent with the actual fault scenario, may have a larger objective function value than a certain FH, H_f, i.e., $E(H_c) > E(H_f)$. In this case, H_c will not be the optimal solution of the established optimization problem, and hence a false diagnosis result could be obtained. Fortunately, with rapid development of communication technologies, the occurrence probability of alarm missing owing to communication channel failures could be significantly decreased.

TABLE VII
REPORT OF THE DIAGNOSIS RESULT

The Diagnosis Result Report	
Occurrence Time	16:10:35 September 18, 2008
Outage Area	L2417, L2419, L2420, L2219, L2244, L2413, L2328, T1, B5, B9, B11
Fault Sections	L2417
Malfunction PRs	Licheng Substation: BFP of CB2219-1 (Operate incorrectly)
Malfunction CBs	Zengcheng Substation: CB2417-1 (Failed to be tripped off)
Missing Alarms	-
Incorrect Alarms	-

VIII. CONCLUSIONS

Based on the existing analytic model-based methods, a novel analytic model is presented for power system fault diagnosis with malfunctions of PRs and CBs taken into account. The developed model could not only estimate the fault sections, but also identify the malfunctioned PRs and CBs, as well as the incorrect and missing alarms. With the application of GPS clocks in recent years to synchronize the data acquisition of Sequence of Events (SOE), the time tagging accuracy of about 1 ms could be achieved. A software package is developed for actual applications in power utility companies. It is demonstrated by many actual fault scenarios of an actual power system in China that the developed model is correct, and the method efficient. The proposed method does not employ the temporal information of alarm messages, and this will be our future efforts.

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