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A new approach to fault diagnosis in electrical distribution networks using a genetic algorithm

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In this paper, a new approach to fault diagnosis in electrical distribution network is proposed. The approach is based upon the parsimonious set covering theory and a genetic algorithm. First, based on the causality relationship among section fault, protective relay action and circuit breaker trip, the expected states of protective relays and circuit breakers are expressed in a strict mathematical manner. Secondly, the well developed parsimonious set covering theory is applied to the fault diagnosis problem. A 0-1 integer programming model is then proposed. Thirdly, a powerful genetic algorithm (GA) based method for the fault diagnosis problem is developed by using information on operations of protective relays and circuit breakers. The developed method can deal with any complicated faults, and simultaneously determine faulty sections and any hidden defects in the feeder protection systems. Test results for a sample electrical distribution network have shown that the developed mathematical model for the fault diagnosis problem is correct, and the adopted GA based method is efficient. © 1997 Elsevier Science Limited.

Key words: electrical distribution network, fault diagnosis, genetic algorithm, set covering theory.

1 INTRODUCTION

Fault diagnosis is to identify faulty components (sections) and malfunctioned devices (such as protective relays and circuit breakers) in a power system by using information on operations of protective relays, circuit breakers and some other analog and/or digital measurement signals. Several kinds of methods have so far been developed, such as the logic-based,[1] expert system-based,[2–6] artificial neural network-based[7] and optimization-based[8–10] methods. Of these methods, the expert system-based method is the most established. Up to now, many kinds of expert systems have been developed using the conventional knowledge representation and inference procedure such as the rule based[3,4] and the model based[5,6] approaches. In order to achieve precise inference especially in the complex fault cases, the rule based expert system must involve a great number of production rules describing the complex protection system behavior. Maintenance of the large knowledge base is very difficult. On the other hand, the model based system is easy to maintain, but the inference process is time consuming.

In recent years, the application of artificial neural networks (ANN) to the fault diagnosis problem has become an active research area. These methods treat the fault diagnosis problem as a classification problem, and use the appropriate ANNs such as the back-propagation (BP) model or the Kohonen model to train and estimate.[7] It is very difficult to reasonably specify a sample set, so the correctness of the diagnosis results can not be guaranteed theoretically.

Recently, a sort of new method for the fault diagnosis problem has been developed using optimization techniques.[8–10] The principle behind this kind of method is to formulate the fault diagnosis problem as an optimization problem and use a global optimization method such as Boltzmann machine[8] or genetic algorithms[9,10] (GA) to solve it. Although the work presented in Refs 8–10 is preliminary, simulation results have shown that these kind of methods are of great promise for large scale power systems.

In this paper, a new method for the fault diagnosis in electrical distribution networks is developed. The work presented in Refs 8–10 is further developed and extended to fault diagnosis in electrical distribution networks. Up to now, some methods have been developed for the fault diagnosis in electrical distribution networks.[11–15] Besides the expert system based methods[11–13] which possess the features stated above, and the fuzzy set based method[14] which devotes to model the inexactness and uncertainties of the heuristic knowledge of operators in the control centers, a very interesting and noteworthy method is presented in Ref. 15 for the fault diagnosis problem in electrical distribution networks by using the Prolog based logic programming approach. Although the developed method in Ref. 15 is attractive, it can only deal with single fault cases. In fact, the main difficulty with the fault diagnosis problem is how to deal with complicated fault scenarios correctly and efficiently, such as multiple faults with some malfunctions of protective relays and/or circuit breakers. The objective of this paper is to develop a robust and efficient method to diagnose these complicated faults in electrical distribution networks. The method developed takes the following three main steps. At first, based on the causality relationship among section fault, the protective relay action and the circuit breaker trip, the expected states of protective relays and circuit breakers are expressed in a strict mathematical manner. Secondly, the well developed parsimonious set covering theory[16,17] is applied to the fault diagnosis problem. A 0-1 integer programming model is then developed, which utilizes the operational information of protective relays and the tripping information of circuit breakers. This model can be used to simultaneously diagnose any complicated faults and any hidden defects in the feeder protection systems. Thirdly, a genetic algorithm (GA) is used to solve this 0-1 programming model, which can find multiple globally optimal solutions directly and efficiently in a single run. This method is very suitable for complicated fault scenarios with malfunctions of protective relays and/or circuit breakers. This is because different combinations of fault sections and malfunctions of protective relays and/or circuit breakers may produce the same set of alarms under these circumstances. The main contribution of this paper lies in the development of a new and systematic approach for the fault diagnosis problem in electrical distribution networks.

The remainder of this paper is organized as follows. Section 2 describes the proposed overall fault diagnosis method. In Section 3, the mathematical model for the fault diagnosis problem in electrical distribution networks is formulated. A parsimonious set covering theory based fault diagnosis method is developed in Section 4. Section 5 presents a genetic algorithm (GA) and its application to the fault diagnosis problem. Sections 6 and 7 present the test results and conclusions.

2 THE OVERALL FAULT DIAGNOSIS METHOD

The developed fault diagnosis method for electrical distribution networks includes the following steps:

(a) To input the system data, including the topological structure of the given distribution network, operating states of each device and the reported alarms (i.e. the operation of protective relays and circuit breakers).
(b) To carry out the fault diagnosis with the following:
    (1) to formulate the 0-1 integer programming model as presented in Sections 3 and 4 for the fault diagnosis problem,
    (2) to produce some hypotheses randomly,
    (3) to apply a genetic algorithm (GA), which is presented in Section 5, to search for better hypotheses progressively until one or more hypotheses that can correctly explain the reported alarms have been found.

3 THE MATHEMATICAL MODEL OF THE FAULT DIAGNOSIS PROBLEM

3.1 A brief introduction to electrical distribution networks

Electrical distribution networks can be operated in a ring or radical structure depending on their application. The reliability for power supply in the ring network is higher than that in the radical one. However, the protective device placement in the ring network is more difficult than that in the radical network. Because of these reasons, it is common practice to utilize the ring network for supplying power to highly populated areas and to major load centers, while in rural areas the radical network is widely employed. Due to more complex protective device placement, the fault diagnosis for the ring network is more difficult than that for the radical one. The objective of this paper is mainly to develop a fault diagnosis method for the ring network, but the developed method can also be applied to the radical network after some simplifications. In fact, the fault diagnosis in the radical network is a special and simple case of that in the ring one.

A detailed description of the distribution ring network and its configuration of protective systems is presented in Ref. 15. For the convenience of presentation, an introduction is given in this subsection based upon the work presented in Ref. 15.

Each ring circuit can have two, three or four parallel feeder circuits and each feeder circuit is protected using pilot wires. Each parallel circuit is also protected by an overcurrent relay installed on the busbar of the substation. Power is supplied to the loads through the distribution transformers in ring circuits. Now we use a simple example as shown in Fig. 1 to study the configuration of protection systems in distribution ring networks. The study system is rated at 11 kV.

The various types of faults that may occur in the ring network are busbar fault, feeder fault and transformer fault. The protection systems corresponding to these three types of faults are subsequently described as below.

(1) When a fault occurs at a busbar in the network of Fig. 1, the alarms are indicated by the tripping of the circuit breakers at locations d and e, i.e. CB1 and CB5, due to the action of the overcurrent relays in the substation. When a busbar fault occurs, the fault current is usually much larger than the normal load current. The operating logic of the overcurrent relays is that once the current detected by sensors (current transformers) exceeds the rated value, and it lasts for a specified time, then the overcurrent relays will operate to trip the related circuit breakers in the substation so as to isolate the faults. The busbars are only protected by these overcurrent relays.

(2) When a fault occurs in a feeder, the circuit breakers at both ends of that feeder will normally trip to isolate the fault. This function is implemented by its protection system, i.e. the pilot wires. Normally, the pilot wires are closed loop lines. When a fault occurs in a feeder, the pilot wire corresponding to this feeder will activate a signal to trip the related circuit breakers at both ends of this feeder. For each circuit breaker, there exists a battery for it so as to provide energy to trip the circuit breaker. If the battery suffers a defect, it can not make the related circuit breaker trip even if the pilot wire has activated the tripping signal. If this happens, the overcurrent relays at the substation will function as a backup protection device to trip the related circuit breakers, and as a result isolate the feeder fault. If the pilot wire corresponding to a feeder is broken or open circuited, it may malfunction. In this case, any feeder fault will cause the open circuited pilot wire to activate a tripping signal to the related circuit breakers.

(3) Under normal conditions, a transformer fault at location c (i.e. T3) in Fig. 1, for example, will be isolated through the opening of the transformer circuit breaker CB11 provided that the battery for this circuit breaker is normal. If the battery suffers a defect, it can not make the circuit breaker trip even if a fault has occurred in the transformer. If this happens, the overcurrent relays at the substation will function as a backup protection device to trip the related circuit breakers, and as a result isolate the transformer fault.

From the above description, it is known that if the pilot wires and all batteries are normal, the alarm patterns will be simple. If defects such as battery failures and open circuited pilot-wires exist in a distribution network, the alarm patterns may be much more complex. In the network as shown in Fig. 1, if there is a short-circuit fault in feeder cb and there is a battery defect at c, the feeder circuit breaker at c (i.e. CB7) will remain closed, although the circuit breaker at b (i.e. CB8) on the feeder cb will trip. This then causes the overcurrent relay at location e to operate the circuit breaker CB5. A transformer fault at c will not lead the circuit breaker CB11 to trip if the battery at c is defective. Instead, the overcurrent relays at locations d and e will actuate to operate the circuit breakers CB1 and CB5, respectively. When the pilot-wire in the protection system

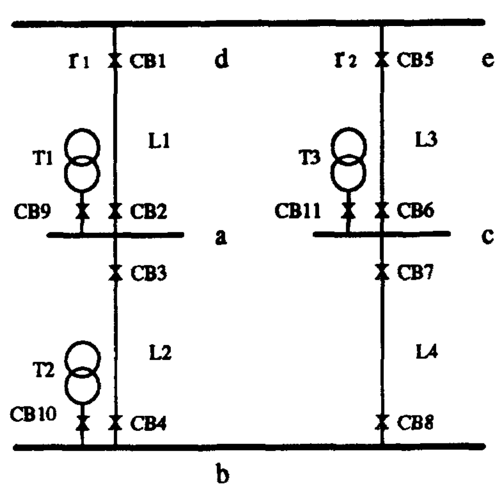

Fig. 1. A simple example.

of the feeder ab is on open-circuit, a feeder fault on cb will lead to tripping of the circuit breakers at locations a and b (i.e. CB3 and CB4) as well as that of the two circuit breakers on feeder cb (i.e. CB7 and CB8).

It should be pointed out that the only available information (alarms) for fault diagnosis in the distribution network is the state of overcurrent relays installed on the busbar of the 11 kV substation and all the circuit breakers in the network. The objective of fault diagnosis in the electrical distribution network is to find the fault sections and the possible hidden defects such as the battery failures and the open-circuited pilot-wires. Thus, the faults are all binary (fault or normal) in nature.

3.2 The expected states of overcurrent relays and circuit breakers

The fault diagnosis problem is to find the hypothesis or hypotheses which can explain the reported alarms reasonably. In other words, when the faults identified by a correct hypothesis or hypotheses occur in a given network, the expected states of protective relays and circuit breakers should be consistent with the reported alarms (i.e. the operations of protective relays and circuit breakers) as much as possible. Thus, a key problem is how to determine the expected states of protective relays and circuit breakers. Fortunately, according to the operating logics of protective relays and circuit breakers, their expected states can be obtained. For the convenience of presentation, we define several symbols first:

n_b, n_f and n_t are the total number of busbars, feeders and transformers in a given distribution system, respectively.

n, n_r, n_c and n_{bf} are the total number of sections, overcurrent relays, circuit breakers and battery locations in a given distribution system, respectively: $n = n_b + n_f + n_t$.

S is a n-dimension vector. The ith element of **S**, s_i, represents the ith section and its state, and $s_i = 0$ or 1 corresponds to its normal or fault state, respectively; **S** is a vector to be determined.
B is a n_{bf}-dimension vector and denotes the battery states; the ith element of **B**, b_i, represents the ith battery and its state, and $b_i = 0$ or 1 corresponds to its normal or failure state, respectively; **B** is also a vector to be determined.
P is a n_{f}-dimension vector and denotes the hidden open-circuited pilot-wires in the feeder protection system; the ith element of **P**, p_i, is used if the pilot-wire corresponding to the ith feeder is open-circuited, is so, then $p_i = 1$, otherwise $p_i = 0$; **P** is also a vector to be determined.
R is a n_{r}-dimension vector and denotes the actual states of the n_{r} overcurrent relays; the kth element of **R**, r_k, represents the kth overcurrent relay and its actual state, and $r_k = 0$ or 1 corresponds to its nonoperational or operational state, respectively.
$\bar{\mathbf{R}}(S)$ is a n_{r}-dimension vector and denotes the expected states of the n_{r} overcurrent relays; the kth element of $\bar{\mathbf{R}}(S)$, $\bar{r}_k(S)$, represents the kth overcurrent relay and its expected state; if the kth overcurrent relay should not operate, then $\bar{r}_k(\mathrm{S})$ should be 0, otherwise it should be 1; $\bar{\mathbf{R}}(\mathbf{S})$ is dependent on **S**.
C is a n_{c}-dimension vector and denotes the actual states of the n_{c} circuit breakers. The jth element of **C**, c_j, represents the jth circuit breaker and its actual state, and $c_j = 0$ or 1 corresponds to its closed (nontripped) or tripped state, respectively.
$\bar{\mathbf{C}}(S,R,B,P)$ is a n_{c}-dimension vector and denotes the expected states of the n_{c} circuit breakers. The jth element of $\bar{\mathbf{C}}(S,R,B,P)$, $\bar{\mathbf{c}}_j(S,R,B,P)$, represents the jth circuit breaker and its expected state. If the jth circuit breaker should not trip, then $\bar{c}_j(S,R,B,P)$ should be 0, otherwise it should be 1. $\bar{\mathbf{C}}(S,R,B,P)$ is dependent on S, R, B and P.

The fault diagnosis problem is to find S, B and P which can explain the reported alarms by utilizing the operation information of overcurrent relays and the tripping information of circuit breakers. Now we use the simple example shown in Fig. 1 to illustrate how to determine $\bar{r}_k(\mathrm{S})$ and $\bar{c}_j(S,R,B,P)$.

The system as shown in Fig. 1 consists of 10 sections, two overcurrent relays and 11 circuit breakers. The 10 sections are composed of three busbars, four feeders and three transformers. The three busbars are a, b and c. It should be pointed out that busbar d-e is not included in these 10 sections. This is because it is a substation busbar, and is protected by the protective devices in the higher voltage grade network. The fault diagnosis for busbar d-e should be included in the transmission network fault diagnosis (which is not the subject of this paper) rather than in the distribution network fault diagnosis.

The four feeders are L1–L4. The three transformers are T1–T3. The 10 sections (s_1–s_{10}) are a, b, c, L1, L2, L3, L4, T1, T2 and T3, respectively. The two overcurrent relays (r_1 and r_2) are the overcurrent relays at locations d and e, respectively. The 11 circuit breakers (c_1–c_{11}) are CB1, CB2, ..., CB11, respectively. There are five battery locations (b_1–b_5), i.e. a, b, c, d and e, sequentially. There are four possible open-circuited pilot-wires (p_1–p_4) in the feeder protection system corresponding to L1–L4, respectively.

It is obvious that for a specified overcurrent relay or circuit breaker, its expected state may be different when different kinds of faults occur. Moreover, it is clear that a specified overcurrent relay or circuit breaker should actuate or trip as long as any kind of fault occurs which can cause it to actuate or trip. Thus, the expected states of overcurrent relays and circuit breakers can be expressed as follows:

$$\bar{r}_i(S) = \mathrm{MAX}[\bar{r}_{bi}(S),\ \bar{r}_{fi}(S),\ \bar{r}_{ti}(S)]\, i = 1,2 \quad (1)$$

$$\bar{c}_i(S,R,B,P) = \mathrm{MAX}[\bar{c}_{bi}(S,R,B,P),\ \bar{c}_{fi}(S,R,B,P),\ \bar{c}_{ti}(S,R,B,P)],\ i = 1,\ldots,8 \quad (2)$$

$$\bar{c}_i(S,R,B,P) = \bar{c}_{ti}(S,R,B,P) \quad i = 9,\ldots,11 \quad (3)$$

where the symbol MAX means to extract the greatest value from the set. The subscripts b, f and t identify busbar faults, feeder faults and transformer faults, respectively, $\bar{r}_{bi}(S)$, $\bar{r}_{fi}(S)$ and $\bar{r}_{ti}(S)$ represent the expected states of the ith overcurrent relay when busbar faults, feeder faults and transformer faults occur, respectively. Similar explanations are applicable to $\bar{c}_{bi}(S,R,B,P)$, $\bar{c}_{fi}(S,R,B,P)$ and $\bar{c}_{ti}(S,R,B,P)$. From eqns (2) and (3), it is shown that the expected state formulations of CB9–CB11 are different from those of CB1–CB8. This is because that the expected states of CB9–CB11 are only dependent on the states (normal or fault) of the related transformers, while the expected states of CB1–CB8 are dependent on the states of the busbars, feeders and transformers. Thus, the current problem is how to determine the terms on the right hand sides of eqns (1)–(3), which will be dealt with below sequentially.

From Fig. 1, it is known that the circuit breakers connected directly to the substation busbar, i.e. CB1 or CB5, can be tripped by the operation of either the pilot-wire protection of the related feeders (L1 or L3) or the overcurrent relays (r_1 or r_2). The states of the overcurrent relays are available, while the states of the pilot-wire protections are not available. If we can discriminate between which kind of protection causes the tripping of these circuit breakers, it will facilitate the formulation of the expected states of the overcurrent relays and these circuit breakers. A simple method is adopted, and is clarified using the following example. If the actuating of r_1 and the tripping of CB1 are both present in the reported alarms, then the tripping of CB1 must be caused by the actuating of r_1. Thus, the tripping information of CB1 is not necessary for the fault diagnosis in this case, and we delete it from the reported alarms and do not utilize it for the fault diagnosis (this treatment is just for ease of formulation, and does not influence the correctness of the fault diagnosis results). If the tripping of CB1 is present and the operation of r_1 is not present in the reported alarms, then the tripping of CB1 must be caused by the operation of the pilot-wire protection. This information is important in this case and must be utilized in the fault diagnosis. In this way, it is very easy to know whether the tripping of these circuit breakers is caused by the pilot-wire protections or by the overcurrent relays. This method is also used in Ref. 15 implicitly.

3.2.1 Busbar fault

A busbar fault causes actuating of the overcurrent relays at locations d and e, provided that all the circuit breakers between this busbar and d, and between this busbar and e are all closed. Thus, we have:

$$\bar{r}_{bi}(S) = \mathrm{MAX}\left\{ s_1\left[1\text{-ONE}\left(\sum_{j=1}^{2} c_j\right)\right], s_2\left[1\text{-ONE}\left(\sum_{j=1}^{4} c_j\right)\right], s_3\left[1\text{-ONE}\left(\sum_{j=1}^{4} c_j + \sum_{j=7}^{8} c_j\right)\right]\right\} \quad (4)$$

$$\bar{r}_{b2}(S) = \mathrm{MAX}\left\{ s_1\left[1\text{-ONE}\left(\sum_{j=3}^{8} c_j\right)\right], s_2\left[1\text{-ONE}\left(\sum_{j=5}^{8} c_j\right)\right], s_3\left[1\text{-ONE}\left(\sum_{j=5}^{6} c_j\right)\right]\right\} \quad (5)$$

where ONE(x) means that if x if equal to or greater than 1, then ONE(x) = 1, otherwise ONE(x) = 0.

When the pilot-wire in the protection system of any feeder is broken, any busbar fault may cause the two circuit breakers on the feeder to trip, provided that no battery failures exist at any of the two terminal busbars. Thus, we have:

$$\bar{c}_{b1}(S,R,B,P) = p_1(1\text{-}b_4)\mathrm{ONE}(s_1+s_2+s_3) \quad (6)$$

$$\bar{c}_{b2}(S,R,B,P) = p_1(1\text{-}b_1)\mathrm{ONE}(s_1+s_2+s_3) \quad (7)$$

$$\bar{c}_{b3}(S,R,B,P) = p_2(1\text{-}b_1)\mathrm{ONE}(s_1+s_2+s_3) \quad (8)$$

$$\bar{c}_{b4}(S,R,B,P) = p_2(1\text{-}b_2)\mathrm{ONE}(s_1+s_2+s_3) \quad (9)$$

$$\bar{c}_{b5}(S,R,B,P) = p_3(1\text{-}b_5)\mathrm{ONE}(s_1+s_2+s_3) \quad (10)$$

$$\bar{c}_{b6}(S,R,B,P) = p_3(1\text{-}b_3)\mathrm{ONE}(s_1+s_2+s_3) \quad (11)$$

$$\bar{c}_{b7}(S,R,B,P) = p_4(1\text{-}b_3)\mathrm{ONE}(s_1+s_2+s_3) \quad (12)$$

$$\bar{c}_{b8}(S,R,B,P) = p_4(1\text{-}b_2)\mathrm{ONE}(s_1+s_2+s_3) \quad (13)$$

3.2.2 Feeder fault

A feeder fault is normally isolated by the circuit breakers at its two ends provided that the batteries at these two locations are normal. Moreover, when a fault occurs on feeder i, and the pilot-wire in the protection system of feeder j is broken, then the circuit breakers at the two ends of feeder j will also trip provided that the batteries at these two locations are normal. Thus, we have:

$$\bar{c}_{f1}(S,R,B,P) = \mathrm{ONE}\{[s_4+(s_5+s_6+s_7)\times p_1]\}(1\text{-}b_4) \quad (14)$$

$$\bar{c}_{f2}(S,R,B,P) = \mathrm{ONE}\{[s_4+(s_5+s_6+s_7)\times p_1]\}(1\text{-}b_1) \quad (15)$$

$$\bar{c}_{f3}(S,R,B,P) = \mathrm{ONE}\{[s_5+(s_4+s_6+s_7)\times p_2]\}(1\text{-}b_1) \quad (16)$$

$$\bar{c}_{f4}(S,R,B,P) = \mathrm{ONE}\{[s_5+(s_4+s_6+s_7)\times p_2]\}(1\text{-}b_2) \quad (17)$$

$$\bar{c}_{f5}(S,R,B,P) = \mathrm{ONE}\{[s_6+(s_4+s_5+s_7)\times p_3]\}(1\text{-}b_5) \quad (18)$$

$$\bar{c}_{f6}(S,R,B,P) = \mathrm{ONE}\{[s_6+(s_4+s_5+s_7)\times p_3]\}(1\text{-}b_3) \quad (19)$$

$$\bar{c}_{f7}(S,R,B,P) = \mathrm{ONE}\{[s_7+(s_4+s_5+s_6)\times p_4]\}(1\text{-}b_3) \quad (20)$$

$$\bar{c}_{f8}(S,R,B,P) = \mathrm{ONE}\{[s_7+(s_4+s_5+s_6)\times p_4]\}(1\text{-}b_2) \quad (21)$$

A feeder fault will cause the overcurrent relays at locations d and e to actuate, as long as all the circuit breakers between this feeder and d, and between this feeder and e are all closed. Thus, we have:

$$\bar{r}_{f1}(S) = \mathrm{MAX}\left\{ s_4(1-c_1), s_5\left[1\text{-ONE}\left(\sum_{j=1}^{3} c_j\right)\right], s_6\left[1\text{-ONE}\left(\sum_{j=1}^{4} c_j + \sum_{j=6}^{8} c_j\right)\right], s_7\left[1\text{-ONE}\left(\sum_{j=1}^{4} c_j + c_8\right)\right]\right\} \quad (22)$$

$$\bar{r}_{f2}(S) = \mathrm{MAX}\left\{ s_4\left[1\text{-ONE}\left(\sum_{j=2}^{8} c_j\right)\right], s_5\left[1\text{-ONE}\left(\sum_{j=4}^{8} c_j\right)\right], s_6(1-c_5), s_7\left[1\text{-ONE}\left(\sum_{j=5}^{7} c_j\right)\right]\right\} \quad (23)$$

3.2.3 Transformer fault

A transformer fault is normally isolated by the transformer circuit breaker provided that the battery at its location is normal. Thus, we have:

$$\bar{c}_{t9}(S,R,B,P) = s_8(1-b_1) \quad (24)$$

$$\bar{c}_{t10}(S,R,B,P) = s_9(1-b_2) \quad (25)$$

$$\bar{c}_{t11}(S,R,B,P) = s_{10}(1-b_3) \quad (26)$$

A transformer fault causes actuating of the over-current relays at locations d and e, provided that the battery at its location has failed, and all the circuit breakers between the busbar to which the transformer is connected directly and d, and between this busbar and e are all closed. Thus, we have:

$$\bar{r}_{t1}(S) = \mathrm{MAX}\left\{ s_8 b_1 \left[1\text{-ONE}\left(\sum_{j=1}^{2} c_j \right) \right], s_9 b_2 \left[1\text{-ONE}\left(\sum_{j=1}^{4} c_j \right) \right], s_{10} b_3 \left[1\text{-ONE}\left(\sum_{j=1}^{4} c_j + \sum_{j=7}^{8} c_j \right) \right] \right\} \quad (27)$$

$$\bar{r}_{t2}(S) = \mathrm{MAX}\left\{ s_8 b_1 \left[1\text{-ONE}\left(\sum_{j=3}^{8} c_j \right) \right], s_9 b_2 \left[1\text{-ONE}\left(\sum_{j=5}^{8} c_j \right) \right], s_{10} b_3 \left[1\text{-ONE}\left(\sum_{j=5}^{6} c_j \right) \right] \right\} \quad (28)$$

When the pilot-wire in the protection system of any feeder is broken, any transformer fault may cause the circuit breakers on the feeder to trip, provided that the battery at the location to which the transformer is connected directly has failed, and no battery failure exists at any of the two terminal busbars of that feeder. Thus, we have:

$$\bar{c}_{t1}(S,R,B,P) = p_1(1-b_4)\mathrm{ONE}(s_8 b_1 + s_9 b_2 + s_{10} b_3) \quad (29)$$

$$\bar{c}_{t2}(S,R,B,P) = p_1(1-b_1)\mathrm{ONE}(s_8 b_1 + s_9 b_2 + s_{10} b_3) \quad (30)$$

$$\bar{c}_{t3}(S,R,B,P) = p_2(1-b_1)\mathrm{ONE}(s_8 b_1 + s_9 b_2 + s_{10} b_3) \quad (31)$$

$$\bar{c}_{t4}(S,R,B,P) = p_2(1-b_2)\mathrm{ONE}(s_8 b_1 + s_9 b_2 + s_{10} b_3) \quad (32)$$

$$\bar{c}_{t5}(S,R,B,P) = p_3(1-b_5)\mathrm{ONE}(s_8 b_1 + s_9 b_2 + s_{10} b_3) \quad (33)$$

$$\bar{c}_{t6}(S,R,B,P) = p_3(1-b_3)\mathrm{ONE}(s_8 b_1 + s_9 b_2 + s_{10} b_3) \quad (34)$$

$$\bar{c}_{t7}(S,R,B,P) = p_4(1-b_3)\mathrm{ONE}(s_8 b_1 + s_9 b_2 + s_{10} b_3) \quad (35)$$

$$\bar{c}_{t8}(S,R,B,P) = p_4(1-b_2)\mathrm{ONE}(s_8 b_1 + s_9 b_2 + s_{10} b_3) \quad (36)$$

It should be pointed out that in the above procedure of formularization, we implicitly adopt the following assumption: the occurrence of each fault is independent of the occurrence of any other faults, or in other words, the occurrence of each fault does not limit the possible occurrence of any other faults simultaneously or almost simultaneously. This is a reasonable assumption in electrical distribution network fault diagnosis, and has been implicitly adopted by all relevant research work.[1–15]

4 FAULT DIAGNOSIS BASED ON THE PARSIMONIOUS SET COVERING THEORY

4.1 The set covering theory for the fault diagnosis problem

As stated in Subsection 3.2, the fault diagnosis problem is to find the most probable hypothesis (or hypotheses) that can explain the alarm information (i.e. the operation of protective relays and circuit breakers). Thus, some criteria should be specified to reflect how well a hypothesis or hypotheses can explain a set of reported alarms, or in other words, how to define the word 'explain'.

One of the leading theories for the fault diagnosis problem in AI community is based upon the notion of parsimoniously covering a set of reported alarms, R and C. The premise of the parsimonious covering theory is that a reasonable diagnosis hypothesis must be a cover of R and C in order to account for the presence of all alarms in R and C.[16,17] On the other hand, not all covers of R and C are equally plausible as hypotheses for a given problem. The principle of parsimony, or 'Occam's razor', is adopted as a criterion of plausibility: a 'simple' cover is preferred to a 'complex' one. Therefore, a plausible hypothesis, or an explanation of R and C, is defined as a parsimonious cover of R and C, i.e. a set of fault sections that covers R and C and satisfies some notion of being parsimonious or 'simple'. Thus, an essential problem in this theory is: what is the nature of 'parsimony' or 'simplicity'? or in other words, what makes one cover of R and C more plausible than another? Mathematically, this problem is equivalent to how to define a suitable criterion to describe 'parsimony'. Up to now, several different criteria have been proposed,[17] such as: (1) single fault restriction: a cover S_I of R and C is an explanation if it contains only a single fault section; (2) relevancy: a cover S_I of R and C is an explanation if it only contains fault sections that causally associate with at least one of the alarms in R and C; (3) irredundancy: a cover S_I of R and C is an explanation if it has no proper subsets which also cover R and C, i.e. removing any section from S_I results in a non-cover of R and C; (4) minimality: a cover S_I of R and C is an explanation if it has the minimal cardinality among all covers of R and C, i.e. it contains the smallest possible number of fault sections needed to cover R and C.

The single fault restriction criterion is not suitable for fault diagnosis in electrical distribution networks, because multiple section faults may happen simultaneously. On the other hand, the relevancy criterion is not a good one for our problem, because it is too loose and may result in many solutions. The irredundancy criterion is generally quite an attractive one. Unfortunately, there are two difficulties with directly generating the set of all irredundant covers.[17] First, this set may itself be quite large in some applications, and may contain many explanations (solutions) of very little probability. Second, and more serious, it may still miss identifying the most reasonable solutions in some cases. The minimality criterion is intuitively a reasonable criterion, because the occurring probability of complex faults is generally smaller than that of simple faults. A modified minimality criterion is adopted in this paper, which will be clarified below.

4.2 The objective function of the fault diagnosis problem

For the fault diagnosis problem, we define a modified minimality criterion as follow:

$$\begin{aligned}\text{Minimize } E(S,B,P) = {} & k_1 \times (|\nabla\mathbf{R}| + |\nabla\mathbf{C}|) \\ & + k_2 \times (|\Delta\mathbf{R}| + |\Delta\mathbf{C}|) \\ & + k_3 \times (|S| + |B| + |P|) \qquad (37)\end{aligned}$$

where

$\Delta\mathbf{R}$ is an n_r-dimension vector, and $\Delta\mathbf{R} = \mathbf{R} - \bar{\mathbf{R}}(S)$,
$\Delta\mathbf{C}$ is an n_c-dimension vector, and $\Delta\mathbf{C} = \mathbf{C} - \bar{\mathbf{C}}(S,R,B,P)$,
$\nabla\mathbf{R}$ is a n_r-dimension vector, and is determined using the following method: if the jth element of $\mathbf{R}$ is zero, then set the jth element in $\nabla\mathbf{R}$ to be 0; if the jth element of $\mathbf{R}$ and $\bar{\mathbf{R}}(S)$ are both 1, then set the jth element in $\nabla\mathbf{R}$ to be 0, otherwise set it to be 1,
$\nabla\mathbf{C}$ is a n_c-dimension vector, and is determined using the following method: if the jth element of $\mathbf{C}$ is zero, then set the jth element in $\nabla\mathbf{C}$ to be 0; if the jth element of $\mathbf{C}$ and $\bar{\mathbf{C}}(S,R,B,P)$ are both 1, then set the jth element in $\nabla\mathbf{C}$ to be 0, otherwise set it to be 1,
$|\nabla\mathbf{R}|$, $|\nabla\mathbf{C}|$, $|\Delta\mathbf{R}|$, $|\Delta\mathbf{C}|$, $|\mathbf{S}|$, $|\mathbf{B}|$ and $|\mathbf{P}|$ are the number of nonzero elements in vectors $\nabla\mathbf{R}$, $\nabla\mathbf{C}$, $\Delta\mathbf{R}$, $\Delta\mathbf{C}$, $\mathbf{S}$, $\mathbf{B}$ and $\mathbf{P}$, respectively.

$|\nabla\mathbf{R}| + |\nabla\mathbf{C}|$ is a criterion to reflect if a solution of (37) is a cover of R and C. If yes, $|\nabla\mathbf{R}| + |\nabla\mathbf{C}| = 0$ otherwise $|\nabla\mathbf{R}| + |\nabla\mathbf{C}|$ reflects the proximity of a solution to a cover. The smaller is $|\nabla\mathbf{R}| + |\nabla\mathbf{C}|$, the more proximate to a cover is the solution; $|\Delta\mathbf{R}| + |\Delta\mathbf{C}|$ reflects the inconsistency between the reported alarms and expected states of overcurrent relays and circuit breakers corresponding to a solution of (37). The smaller is $|\Delta\mathbf{R}| + |\Delta\mathbf{C}|$, the more consistent are the expected states and the reported alarms. They are fully consistent when $|\Delta\mathbf{R}| + |\Delta\mathbf{C}| = 0$; $|\mathbf{S}| + |\mathbf{B}| + |\mathbf{P}|$ represents the number of fault sections and hidden defects. The three terms on the right hand side of (37) respectively reflect the following three requirements for a solution or solutions to the fault diagnosis problem:

(a) At first, the solution or solutions should be a cover or covers of R and C.
(b) Secondly, the expected states of overcurrent relays and circuit breakers corresponding to a solution or solutions should be consistent with the reported alarms as much as possible.
(c) Thirdly, the solutions with minimum number of fault sections and hidden defects are preferred to more complex explanations.

In eqn (37) k_1–k_3 are positive weighting coefficients to reflect the relative importance of these three requirements. It is our opinion that the priorities of these three requirements should decline progressively, so k_1–k_3 should be specified to decrease successively; k_1 should be big enough, and be specified as the biggest amongst these three coefficients to ensure that the solution or solutions of (37) are covers of R and C. The scaling of eqn (37) is not a difficult problem, as long as the following condition is satisfied: $k_1 >> k_2 >> k_3$. Specifically, if we set $k_3 = 1$, then k_2 should be specified larger than the maximum possible number of simultaneously occurring fault sections and hidden defects (for example $k_2 = 10$ is large enough), in other words, k_2 should be specified larger than the maximum possible value of $|\mathbf{S}| + |\mathbf{B}| + |\mathbf{P}|$, and k_1 should be specified larger than the maximum possible value of $k_2 \times (|\Delta\mathbf{R}| + |\Delta\mathbf{C}|)$. For a given distribution network, the maximum value of $|\Delta\mathbf{R}| + |\Delta\mathbf{C}|$ can be easily determined, i.e. the total number of overcurrent relays and circuit breakers. Following these scaling guidelines, correct results can be guaranteed mathematically, but these guidelines are conservative (this means that k_1 and k_2 may need not be so large). For example, k_1, k_2 and k_3 can be respectively specified to be 1000, 10 and 1 for the test distribution network presented in Section 6.

The remaining problem is how to estimate the faulty section(s) and hidden defect(s) by utilizing eqn (37) and the reported alarms (i.e. R and C), or in other words, how to find **S**, **B** and **P** which minimize $\mathbf{E}(S,B,P)$. This is a 0-1 integer programming problem. In the following section, we will introduce a genetic algorithm (GA) to solve this problem. The motivation for adopting the GA for solving this problem lies in its ability for finding global optimal solution(s) efficiently.

It should be pointed out that the minimization of $\mathbf{E}(S,B,P)$ can also be solved by using a conventional integer programming method, such as the branch and bound method or the Lagrangian relaxation method. Up to now, some special classes of 0-1 integer programming problems have been efficiently solved by operations research and mathematical programming solution techniques.[18] However, the fault diagnosis problem does not apparently fall into any of these special cases. In addition, the fault diagnosis problem

```
Initialize the parameters of the genetic algorithm;
Randomly generate the old_population;
For generation L:= 1 to max_generation
Compute the fitness of each individual in the old_population;
Copy the highest fitness of individual to the solution_vector;
Use tournament selection method to form mating_pool;
While the number_of_individual < population_size do
   select two parents from the mating_pool randomly;
   perform the crossover of the parents to produce two offspring;
   mutate each offspring based on mutation_probability;
   place the offspring to new_population;
Endwhile
Replace the old_population by the new_population;
Endfor
Print out the solution_vector as the final solution
```

Fig. 2. The outline of a typical genetic algorithm (in pseudo Pascal form).

can have multiple optimal solutions and must be fast enough for on-line applications, thus the conventional integer programming methods, such as the branch and bound method, are unlikely to be very suitable. In recent years, there has been an enormous amount of interest in the applications of genetic algorithms (GA)[18–21], simulated annealing (SA)[22,23] and tabu search (TS)[24–26] for solving some difficult or poorly characterized optimization problems of a multi-modal or combinatorial nature. Many successful applications of these methods in solving large scale practical problems have been reported recently; SA is powerful in obtaining the optimal solutions but its computation burden is heavy, so it is suitable for some planning problems which are not time critical. The fault diagnosis problem is a time critical problem, thus SA is not a good candidate for solving this problem; GA has been demonstrated to be able to solve the set covering problem efficiently in Ref. 18, and its computation speed is faster than that of SA. Moreover, some optimization programs based on GA are able to solve very large scale and complex problems and can find multiple globally optimal solutions in a single run, so GA is selected for this application. Recently, TS has emerged as a new, highly efficient, search paradigm for quickly finding high quality solutions to combinatorial optimization problems, but its application to power systems is just starting and its computational efficiency remains to be investigated. It will be a future topic to explore TS's application in the fault diagnosis problem of electrical distribution networks.

In genetic algorithms, the fitness function (i.e. the objective function) is maximized and positive. Thus, the following fitness function is used in solving the fault diagnosis problem by genetic algorithms,

$$f(S, B, P) = W - E(S, B, P) \tag{38}$$

where W is specified as a very large positive constant which is used to guarantee the fitness function to be positive, and $W = 10^6$ is used in this work.

5 A GENETIC ALGORITHM AND ITS APPLICATION TO THE FAULT DIAGNOSIS PROBLEM

Genetic algorithms (GA)[18–21] are search procedures whose mechanics are based on those of natural genetics. In this paper, it is used to solve the maximization problem of eqn (38).

A typical genetic algorithm is shown in Fig. 2, and some points associated with the genetic algorithm are described as follows:

(a) There are many methods to select two parents from the old population, and different GA methods can be obtained by using different selection methods. In this GA, the tournament selection[10,18,20] is employed.

(b) When GA is used to solve an optimization problem, it is necessary to encode the solution in a string form. Generally, the binary encoding method is used. The crossover and mutation are operating on the strings to search for optimal solutions. The solution to the fault diagnosis problem in the electrical distribution network is encoded as a binary string $ST = (S, B, P)$ directly. This expression means that the first n bits in ST correspond to the elements in S sequentially, the $n+1$ bit through $n + n_{bf}$ bit in ST correspond to the elements in B sequentially, and the $n + n_{bf} + 1$ bit through $n + n_{bf} + n_p$ bit in ST correspond to the elements in P sequentially.

(c) Crossover is the most important operator in GA, and it is applied with probability which is typically between 0·6 and 0·9. The crossover operator takes two strings from the old population and exchanges some contiguous segment of their structures to form two offspring. There are several different crossover operators, such as the one-point crossover,[19] two-point crossover[18] and uniform crossover.[18] The uniform crossover is more powerful in exploring the solution space than the one-point crossover and two-point crossover, so it is adopted in this work.

(d) Mutation is also an important operator of GA. In a binary encoded GA, the mutation operator randomly switches one or more bits with some small probability which is typically between 0·001 and 0·1.

(e) The variable probability techniques[18,21] are applied to the crossover and mutation operators in the GA. Initially, a probability for each is entered. For every generation thereafter, the probability of crossover is linearly decreased while the probability of mutation is linearly increased. From the computational mechanism of GA, the probability of crossover should be decreased and the probability of mutation should be increased in order to increase the computational efficiency and the opportunities to find optimal solutions.[18] Limits on these probabilities must be set so that they do not exceed the permitted intervals. In this paper, the permitted interval for P_c is between 0·6 and 0·9, and for P_m, it is between 0·001 and 0·1; P_c and P_m are changed from generation to generation according to the following

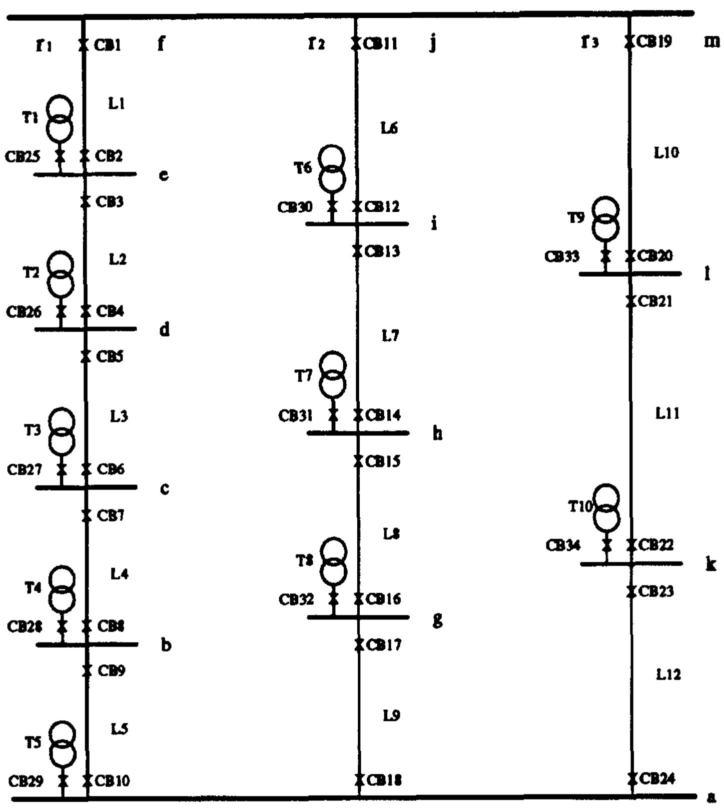

Fig. 3. The sample electrical distribution network.

equations:

$$P_c^{(t)} = P_c^{(t-1)} - \left[P_c^{(0)} - 0{\cdot}6\right]/MG \tag{39}$$

$$P_m^{(t)} = P_m^{(t-1)} + \left[0{\cdot}1 - P_m^{(0)}\right]/MG \tag{40}$$

where t denotes the number of the generation (i.e. the iteration number), MG is the maximum permitted generation number, $P_c^{(0)}$ and $P_m^{(0)}$ denote the initial values of the crossover probability and the mutation probability, respectively, $P_c^{(t)}$ and $P_m^{(t)}$ denote the crossover probability and the mutation probability at the tth generation, respectively. In this work $P_c^{(0)}$ and $P_m^{(0)}$ are set to be 0·9 and 0·001, respectively.

The GA as stated above is powerful in finding the global or near global optimal solution of an optimization problem. But it is shown from the simulation results that the GA can usually find only one global or near global optimal solution. For the fault diagnosis problem, multiple solutions may exist especially for complex fault cases. In order to find all reasonable solutions, the GA must be modified.[9] The modification is as follows. At the first generation, we pick a copy for each of the best solutions from the population and store them in a specially designed array. In each of the follow-up generations, we check if the best solutions in the current population are better than the solutions stored in the array. If yes, we use the best solutions in the current generation to replace the record of the array. If the best solutions in the current population are as good as the solutions stored in the array and they are not the same solutions, then we put the best solutions in the current generation into the array, thus the array is expanded. Otherwise we do not change the record of the array. Note that the array only contains those solutions which are found to be the best up to the current generation, and only a copy can be stored in the array for each of the best solutions. Thus, at the end of the GA operation, the array will contain all the different best solutions found during the operation. If the parameters of GA (for example, population size, MG, P_c and P_m) are properly specified, multiple global optimal solutions can be found in this way. This has been verified by the following numerical example.

6 TEST RESULTS

We have used a larger sample distribution from Ref. 15 as shown in Fig. 3 to test the method developed for the fault diagnosis problem. This system consists of 32 sections, three overcurrent relays and 34 circuit breakers. The 32 sections are composed of 10 busbars, 12 feeders and 10 transformers. The 10 busbars are a, b, c, d, e, g, h, i, k and l. The 12 feeders are L1–L12. The 10 transformers are T1–T10. The 32 sections (s_1–s_{32}) are a, b, c, d, e, g, h, i, k, l, L1, L2, L3, L4, L5, L6, L7, L8, L9, L10, L11, L12, T1, T2, T3, T4, T5, T6, T7, T8, T9 and T10, respectively. The three overcurrent relays (r_1–r_3)

Table 1. Test results of the sample electrical distribution network

Test No.	The alarm signals	The estimated faulty sections, battery failures and open circuited pilot wires
1	Actuated relays: r_2 and r_3 Tripped circuit breaker: CB7	Faulty section: L4; Battery failure: b
2	Actuated relay: r_1 Tripped circuit breaker: CB4	Faulty section: L2; Battery failure: e
3	Actuated relay: r_2 Tripped circuit breakers: CB3, CB21 and CB22	There are two solutions: 1. Faulty sections: L2 and L11; Battery failure: d 2. Faulty section: L2; Battery failure: d; Open circuited pilot wire: L11
4	Tripped circuit breakers: CB3, CB7 and CB8	There are two solutions: 1. Faulty sections: L2 and L4; Battery failure: d 2. Faulty section: L2; Battery failure: d Open circuited pilot wire: L4
5	Actuated relays: r_1 and r_3 Tripped circuit breaker: CB15	Faulty section: L8; Battery failure: g
6	Actuated relay: r_3 Tripped circuit breakers: CB23 and CB24	There are four solutions: 1. Faulty sections: l and L12 2. Faulty sections: k and L12 3. Faulty section: l Open circuited pilot wire: L12 4. Faulty section: k Open circuited pilot wire: L12
7	Tripped circuit breakers: CB7, CB8, CB13, CB14, CB23 and CB24	There are seven solutions: 1. Faulty sections: L4, L7 and L12 2. Faulty sections: L4 and L7 Open circuited pilot wire: L12 3. Faulty sections: L7 and L12 Open circuited pilot wire: L4 4. Faulty sections: L4 and L12 Open circuited pilot wire: L7 5. Faulty sections: L4 Open circuited pilot wires: L7 and L12 6. Faulty sections: L7 Open circuited pilot wires: L4 and L12 7. Faulty sections: L12 Open circuited pilot wires: L4 and L7
8	Actuated relay: r_2 Tripped circuit breakers: CB17 and CB18	There are six solutions: 1. Faulty sections: g and L9 2. Faulty sections: h and L9 3. Faulty sections: i and L9 4. Faulty section: g Open circuited pilot wire: L9 5. Faulty section: h Open circuited pilot wire: L9 6. Faulty section: i Open circuited pilot wire: L9
9	Actuated relays: r_1 and r_3 Tripped circuit breakers: CB6 and CB13	Faulty sections: L3 and L7; Battery failures: d and h
10	Actuated relay: r_2 Tripped circuit breakers: CB3, CB4, CB16 and CB34	There are two solutions: 1. Faulty sections: T10, L2 and L8; Battery failure: h 2. Faulty sections: T10 and L8: Battery failure: h Open circuited pilot wire: L2

are the overcurrent relays at locations f, j and m, respectively. The 34 circuit breakers (c_1–c_{34}) are CB1, CB2, …, CB34, respectively. There are 13 battery locations (b_1–b_{13}), i.e., a, b, c, d, e, f, g, h, i, j, k, l and m. There are 12 possible open-circuited pilot-wires (p_1–p_{12}) in the feeder protection system corresponding to L1–L12, sequentially.

More than 50 fault scenarios have been tested. Among them, some fault scenarios are due to a single section fault and the corresponding protective relay(s) correctly actuated to successfully trip the related circuit breakers. The others are complicated fault scenarios which consist of cases of malfunction of protective relays and/or circuit breakers for single section fault cases and multiple section fault cases. In terms of the actuating logics of the protective relays, all the results on fault diagnosis are correct. Due to space limitation, only the detailed results for 10 complicated faults rather than single faults are shown in Table 1.

The simulation results show that the proposed method can be applied to multiple section fault cases and to the cases with battery failures and/or open-circuited pilot-wires in the protection system of feeders. The optimal solutions for all test cases of the sample distribution system can be obtained by setting the parameters in GA as follows:

Population size $(PS) = 500$; the maximum permitted iteration number $(MG) = 30$; the initial crossover probability $(P_c^{(0)}) = 0{\cdot}9$; the initial mutation probability $(P_m^{(0)}) = 0{\cdot}001$ and the stop criterion is that the maximum permitted iteration number has been reached.

In addition, the computing time for each test case of the sample distribution system is about 1·5 min on a 486 microcomputer, so the proposed GA-based method for the fault diagnosis is of potential for on-line fault diagnosis in actual electrical distribution networks.

The main advantages of the proposed method over the one presented in Ref. 15 and other expert system based methods are that the proposed method is mathematically sound. The proposed method can be used to diagnose any complicated fault cases, and can find multiple globally optimal solutions directly and efficiently in a single run.

7 CONCLUSIONS

In this paper, a new method for fault diagnosis in electrical distribution networks is presented based on the set covering theory and genetic algorithm. Firstly, a 0-1 integer programming model is developed for the fault diagnosis problem, which utilizes the operational information of protective relays and the tripping information of circuit breakers. This developed model is mathematically sound, and can be used to diagnose any arbitrarily complicated fault scenarios and hidden battery failures and open-circuited pilot-wires simultaneously. Then, a genetic algorithm is adopted for solving this 0-1 integer programming model, which can find the multiple globally optimal solution(s) efficiently in a single run. Finally, the developed method is applied to a sample distribution system, and it is shown by many test results that the method is correct and efficient. Moreover, the method is fast and flexible, and of potential for on-line fault diagnosis in actual electrical distribution networks.

The main contribution of this paper lies in the development of a new and systematic method for the fault diagnosis problem in electrical distribution networks. Further work will be done to test the developed method for larger distribution systems.

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