AN EXPERT SYSTEM FOR LOCATING DISTRIBUTION SYSTEM FAULTS

Yuan-Yih Hsu, F. C. Lu, Y. Chien
Department of Electrical Engineering
National Taiwan University
Taipei, Taiwan, ROC

J. P. Liu, J.T. Lin
Power Research Laboratory
Taiwan Power Company
Taipei, Taiwan, ROC

H.S. Yu, R.T. Kuo
Taipei City District Office
Taiwan Power Company
Taipei, Taiwan, ROC

Abstract – A rule-based expert system is designed to locate the faults in a distribution system. Distribution system component data and network topology are stored in the database. A set of heuristic rules are compiled from the dispatchers' experience and are imbedded in the rule base. To locate distribution system fault, an inference engine is developed to perform deductive reasonings on the rules in the knowledge base. The inference engine comprises three major parts: the dynamic searching method, the backtracing approach, and the set intersection operation. The expert system is implemented on a personal computer using the artificial intelligence language PROLOG. To demonstrate the effectiveness of the proposed approach, the expert system has been applied to locate faults in a real underground distribution system within the service area of Taipei City District Office of Taiwan Power Company. It is found that the expert system can identify fault location very efficiently. Therefore, it can serve as a valuable tool to help distribution system dispatchers determine fault locations.

Keywords: distribution system, expert system, fault location identification

1. INTRODUCTION

To reduce outage time and to enhance service reliability, it is essential for dispatchers to locate the fault in a distribution system as soon as possible. In current practice, heuristic rules from system dispatchers' past experience are heavily relied on in identifying fault locations. The important role of human experts in locating distribution system fault motivated some recent works [1–8] on the application of expert systems to this field.

Most expert systems developed so far for fault diagnosis employed the informations from circuit breakers and relays. Thus, they are suitable for estimating the fault sections on transmission lines or primary distribution feeders which are protected by circuit breakers and relays. For a fault event which takes place in the part of distribution system which is between the primary feeder and customer services, it will be cleared by the fuse at the head of a lateral or a sublateral. The circuit breaker at the head of the primary feeder will not operate for the faults in this part of the distribution system which covers laterals, sublaterals, distribution transformers and the associated devices. Thus, circuit breaker information is not available in the present case, nor is the location of the fuse which blows out.

This paper is concerned with locating the faults on a distribution system between the primary feeder and customer services. The fault events in this part of the system will cause service interruptions to less customers than those on the primary feeder. However, they occur more frequently than their counterparts on the primary feeder. Moreover, this part of the system contains a great number of devices widely spread in a large geographical area. Since there are only limited troublemen and crews on duty in a dispatching center, it is essential for the dispatchers to correctly identify possible fault locations and assign the limited troublemen to the most possible sites to find the particular device out of service and repair the damages. If the troublemen fail to find the device out of service near the locations specified by the dispatchers, the dispatchers will have to make new judgments and ask the troublemen to go somewhere else. In the downtown area of a crowded city such as Taipei, it may take the troublemen more than 30 minutes to get to a place only one mile away. Thus, scarce crews and traffic make fault diagnosis a great challenge to the dispatchers in the Taipei City District Office of Taiwan Power Company (TPC).

Just as in the work of Reference [9], the only information available to the dispatchers in TPC is the trouble calls which are recorded by the telephone operators in customer service center and are sent to the dispatching center through FAX. The dispatchers then use the address of the trouble call and their previous experience to identify fault location. Since the location and connectivity of the devices, such as cable sections, distribution transformers, switches, ... , etc., are not available in current computer database, it is impossible to exactly identify from which distribution transformer the interrupted customer is supplied power. In most cases, the dispatcher has to look up feeder-circuit configuration diagrams and maps and tries to determine the distribution transformers close to the address of the customer who made the phone call. With these distribution transformers at hand, the dispatcher identifies several possible fault locations based on the connectivity from these distribution transformers to other devices in the distribution network. In this decision-making process, the dispatchers' heuristic rules gained from previous operational experience play an important role.

In this paper, an expert system which emulates the behavior of an experienced dispatcher in diagnosing distribution system faults is developed. To free the dispatchers from the laborious work of looking up maps and feeder diagrams, the location and characteristics of each device is stored in the database of the expert system. System configuration is stored using a pointer which points to the upstream device of each component. A set of heuristic rules are compiled through discussions with the experienced dispatchers in the Taipei City District Office of TPC. These rules are coded into computer programs using the artificial intelligence language PROLOG and are stored in the rule base of the expert system. The inference engine, which performs deductive reasonings on the rules to reach the fault location, comprises three major parts: the dynamic searching method, the backtracing approach, and the set intersection operation. The expert system, which is implemented on a personal computer, has been tested on a distribution system within the service area of the Taipei City District Office of TPC. It is found from the test results that the developed expert system is capable of identifying distribution system faults in a very efficient manner.

2. EXPERT SYSTEM STRUCTURE

As shown in Fig. 1, the expert system comprises the knowledge base, the inference engine, and the man-machine interface (MMI).

The knowledge base consists of two major parts: the database and the rule base. The database stores the location and characteristics of a component and the device connected upstream to the component. These data are required by the inference engine to configure the distribution system in the process of locating system fault. The rule base contains the heuristic rules employed by dispatchers to identify fault location. Details of the database and the rule base will be described in Sections 3.1 and 3.2, respectively.

The inference engine is the core of the expert system. It receives the addresses of the customers out of service which are provided by the expert system user through man-machine interface. Using the

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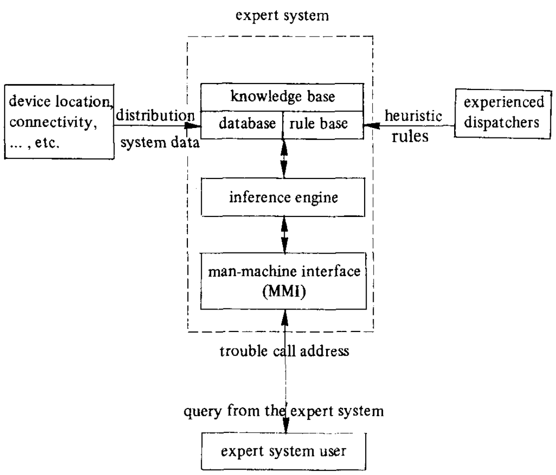


Fig. 1 The structure of the expert system for locating distribution system faults

distribution system data in the database, the heuristic rules in the rule base, and the trouble call addresses, the inference engine identifies fault location through logical reasoning. If necessary, the inference engine may ask the user to do something (e.g. making phone calls) or to key in some other data useful for the inference process. Details of the inference engine will be described in Section 3.3.

The man-machine interface serves as a communication medium between the user and the expert system. With MMI, the user can ask the expert system to identify fault location. The user can also update the data and rules in the knowledge base. On the other hand, the expert system provides fault locations to the user and requests the user to make phone calls through MMI.

3. DESIGN OF THE EXPERT SYSTEM

The design of the expert system begins with compiling distribution system data and storing these data in the database. Then, an interview with experienced dispatchers in TPC is conducted to get the heuristic rules for identifying fault locations. The final step in expert system design is to code the rules and build an inference engine which is capable of performing logical reasonings on the rules in order to estimate the fault location. Details of the database, the rule base, and the inference engine are described as follows.

3.1 The Database

The following data are required in the present work:

(1) Component Data:
The serial number, address and location of each branching point and the switches, fuses, and distribution transformers at each branching point.
(2) Feeder circuit configuration diagrams.
(3) Key Customer Data:
The addresses and telephone numbers of key customers such as hospitals, hotels, department stores, major buildings, ... , etc.
(4) The distribution transformers which are often overloaded.
(5) The cable sections and distribution transformers which have frequent outage records.
(6) The branching points which are vulnerable to outages caused by rats.

A few comments with regard to these items can be made.

(1) To locate each branching point and each device, the entire service area of Taipei City District of TPC is divided into 6800 squares, with each square block serving an area of 10m × 10m. A two-dimensional rectangular coordinate system is designed to label each square block. The coordinate system is described using the numeric digits 0–9 and English alphabets A–H. The address of each branching point is in Chinese. To facilitate the user to key in and read the Chinese characters, a Chinese input/output interface is imbedded within the MMI of the expert system.
(2) From the feeder circuit configuration diagrams, the branching points connected upstream and downstream to a particular branching point can be identified. To locate the fault in a distribution system of radial structure, only upstream devices are needed since the only path between a branching point and the source (substation) can be traced through upstream devices. But we store downstream devices as well to facilitate our future work on network reconfiguration.
(3) The key customers have technicians who are in charge of electricity supply of the building. They are supposed to notify the TPC service center of any service interruption. In case they fail to do so, the dispatchers can use the available telephone numbers to give them a call to make sure if electricity service is interrupted. In the present work, the addresses and telephone numbers of key customers are stored in the database so that the expert system can request the user to make a phone call to a particular key customer and send the customer's status back to the expert system. In the future, an auto-dial system may be connected to the expert system to perform automatic dialing.
(4) Using the data in items (1)–(3) and the heuristic rules, the inference engine can reach some regions where the fault event can possibly occur. To further narrow down the scope of these possible outage sections, the informations in items (4)–(6) are helpful. These data change with time and are constantly updated by the users to describe current situations.
(5) In a Prolog program, the data are stored in the form of 'facts'. For example, the following Prolog statement represents the fact that customer 1 is out of service.

fact 1: interrupted (customer-1) (1)

As a second example, the following is a prolog statement which represents the fact that point 1 is a branching point.

fact 2: branching (point-1). (2)

The following fact states that point 1 is close to customer 1.

fact 3: close-to (customer-1, point-1). (3)

3.2 The Rule Base

The following heuristic rules have been identified through discussions with experienced dispatchers in TPC.

(1) A customer is usually supplied power from a distribution transformer nearby.
(2) A branching point is supplied power from its upstream branching point.
(3) Since the distribution system is of radial structure, there exists one unique path from the source (substation) to each branching point.
(4) The path comprising the branching point close to the interrupted customer and all upstream branching points forms a region where a fault can possibly occur.
(5) In most cases, the technicians of key customers will report the service interruption of their building.
(6) It's rare to have two outages taking place in the part of distribution system under study at the same time.
(7) Overloaded transformers are vulnerable to outages.
(8) Those branching points which are close to restaurants are very likely to have outages caused by rats.

The aforementioned heuristic rules are written in the form of production rules using the AI language PROLOG. These production rules, which are imbedded in the rule base, are of the following form

If (Premise),
Then (Conclusion). (4)

If the 'Premise' part of eq. (4) is satisfied, then the 'conclusion' part is activated. For example, rule (1) in the rule base can be implemented in PROLOG as follows.

rule 1: is-supplied (X, Y): interrupted (X), branching (Y) close-to (X, Y). (5)

The meaning of eq. (5) is as follows.

If (X is an interrupted customer, and Y is a branching point, and branching point Y is close to customer X),

Then (customer X is supplied power from branching point Y).

Using facts 1–3 (eqs. (1)–(3)) in the database, it is obvious that the Premise of rule 1 is satisfied if variable X is assigned the value customer-1 and variable Y is bound to point-1. Thus, the conclusion of rule 1 will be activated and the new fact of (is-supplied (customer-1, point-1)) is deduced. In other words, the fact that customer-1 is supplied power from point-1 is deduced by expert system by using the production rule in eq. (5) and the facts (or data) in eqs. (1)–(3). Thus, through repeated matching with the 'Premise' parts of the production rules, a set of new facts and data can be derived from the 'Conclusion' parts of the rules. Therefore, it is usually stated that the expert system can reach the final result through repeated deductive reasonings on the production rules.

3.3 The Inference Engine

The process of deriving new facts and the final result through deductive reasonings on the production rules is controlled by the inference engine, which is the core of the expert system. Since a PROLOG program is executed in the order that the facts and rules are stored in the program and by some control statements, an inference engine must be designed by the PROLOG user.

Before we go through the details of the inference engine, the assumption of a single outage event is first made based on rule (6) in the rule base. In other words, we assume in this work that there is only one fault event taking place in the study system at any time.

As shown in Fig. 2, the inference engine begins with reading in the trouble call records provided by the expert system user. Since fault location identification is a very urgent task, a user-friendly Chinese input/output interface is designed [10] to reduce the time required by the user to key in the address of the customer out of service.

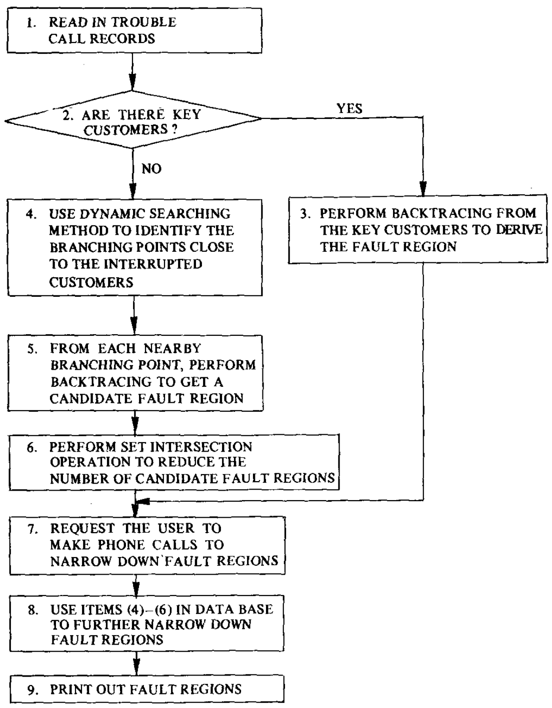


Fig. 2 Procedures followed by the inference engine to identify fault location.

It was mentioned earlier that all customers could be divided into two groups: the group of key customers and that of ordinary customers. We know exaclty to which branching point a key customer is connected. But this is not the case for an ordinary customer. Thus, in block 2 of Fig. 2, the inference engine checks the database to see if there exists any key customer who is out of service. If the answer is yes, it performs backtracing starting from the branching point where the key customer is supplied power to the source (substation). In the backtracing process, all the upstream branching points to the key customer stored in the database are used. Then it is concluded in block 3 that the fault region consists of these upstream branching points and the associated devices (distribution transformers, switches, ... , etc.). The cable sections between branching points are also included in the fault region.

As an example, consider the case where a customer supplied power from branching point 11 in Fig. 3 reported service interruption. The upstream branching points include points 1, 2, 9, and 10. Since we do not consider the faults on primary feeders, the lateral between branching points 2 and 11 is the fault region. Any device or cable section within the fault region is likely to cause the service interruption experienced by the key customer in branching point 11. To be specific, the transformers or switches at branching points 9, 10, and 11 and cable sections 2-9, 9-10, and 10-11 might be the devices out of service.

Let's now turn to the case where there is no key customer in the trouble call records. In this case, we have to guess to which branching point an interrupted customer is connected. From Rule (1) in Section 3.2, it is concluded that this branching point can not be far away from the interrupted customer. Thus, as shown in block 4 of Fig. 2, a dynamic searching method is developed to find the branching points nearly. A brief description of the dynamic searching method is given as follows.

Recall that, in the database, we have the address and location (described by a two-dimensional rectangular coordinate system) of each branching point. But we only have the address of the interrupted customer and this address is usually not the same as the address of any branching point. The major difficulty in locating the branching points close to an interrupted customer is that we do not have the coordinate of the customer. Thus, the dynamic searching method starts with looking for a branching point with an address which is 'close to' the customer address. As an example, let the customer address be (No. 10, Lane 468, Tun-Hua South Road). The address of a branching point which is very 'close to' the customer address is found to be (No. 14, Lane 468, Tun-Hua South Road). The branching point and the customer are located at the same lane of the same road. Even the numbers of the two addresses are very close (#10 and #14). Thus, it can be concluded that this branching point, which is called the central branching point, is close to the customer out of service. Though the customer is not necessarily supplied power from the central branching point, it can be concluded that he must be supplied power from this point or from some other branching points near the central branching point.

Since the location of each branching point is described by a pair of rectangular coordinates in the map, it is possible to find the branching points near the central branching points using these coordinates. In the present study, we consider our candidates to be the branching points which are located within a square block of 100m × 100m, with the central branching point being the center of the square block. Since the range of the square block can be expanded or narrowed down at the request of the expert system user, the method is called the dynamic searching method.

To illustrate this method, consider again the distribution system in Fig. 3. Suppose there are two customers, customer 1 and customer 2, who reported service interruption. We have the addresses of these customers, but we do not know their coordinates in the map. So, we first figure out, from the addresses of the branching points, that the addresses of branching point 7 and branching point 14 are very close to the addresses of customers 1 and 2, respectively. Then, using the coordinate of branching point 7, which is now a central branching point for customer 1, we find out that branching points 4, 5, 7, 10, and 11 are located within square block 1, which is a square block of 100m × 100m, with branching point 7 being the center of the block. Thus, it is concluded that customer 1 is very likely to be supplied power from one of these branching points. In the same manner, we can conclude that customer 2 is supplied power from one of the branching points 6, 8, and 14 within square block 2.

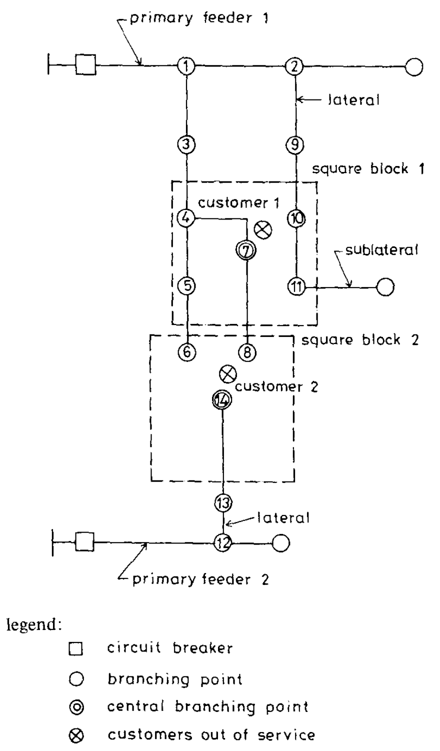


Fig. 3 A small distribution system used as an example to illustrate the inference procedure

With the candidate branching points at hand, we can perform backtracing from these branching points to the substation to get candidate fault regions, as indicated in block 5 of Fig. 2. Consider the system in Fig. 3. We have two sets of possible fault regions, Set 1 and Set 2, corresponding to the two sets of candidate branching points (4, 5, 7, 10, 11) and (6, 8, 14), respectively. Set 1 and Set 2 are given as follows.

$$\text{Set } 1 = \{(1-3-4-5), (1-3-4-7), (2-9-10-11)\}$$
$$\text{Set } 2 = \{(1-3-4-5-6), (1-3-4-7-8), (12-13-14)\}$$

For example, the fault region (1–3–4–5) in Set 1 indicates that the devices in branching points 3, 4, and 5 and cable sections 1–3, 3–4, and 4–5 can be out of service.

In block 6 of Fig. 2, we take set intersection operation on the two sets, set 1 and set 2 to locate the regions common to the two sets. The resultant candidate fault regions are as follows.

Region 1: (1–3–4–5)
Region 2: (1–3–4–7)

The reason for carrying out the intersection operation is based on our previous assumption that there is only one fault event taking place in the study system at any time.

In block 7 of Fig. 2, the expert system tries to further narrow down Region 1 and Region 2 in our previous example by checking the key customer lists in the database to see if there is any key customer in the two regions. The task starts with the branching point nearest to the source. In the present example, the expert system first checks if the address of branching point 3 is the same as that of a key customer. If the answer is yes, the expert system prints out the address and telephone number of the key customer and requests the user to make a phone call to the key customer to see if the customer is out of service. If the customer is indeed out of service, then the fault region is reduced to (1–3). In other words, the devices in branching point 3 and cable section 1–3 are the potential devices out of service. Details of the procedures to narrow down Region 1 and Region 2 are described by the flow chart in Fig. 4. Note that, in blocks 1, 2, 3, and 4 of Fig. 4, the expert system will continue to check if there is any key customer supplied power from branching point 5 or 7 to further narrow down the fault region. The blocks associated with these actions are omitted from Fig. 4 due to limited space.

The fault regions reached in block 7 can be further narrowed down by using items (4)–(6) in the database. For example, if the fault region comprises cable section 1–3 and branching point 3 and cable section 1–3 has frequent outage records, then a fault event is very likely to occur on cable section 1–3. This is what the expert system performs in block 8 of Fig. 2.

The addresses of the devices and the connectivity of the devices in the final fault region reached by the expert system are depicted in the user's terminal. A typical display will be shown in next section.

4. IMPLEMENTATION OF THE EXPERT SYSTEM

The expert system has been implemented on a personal computer. It is written in the AI language PROLOG. There are approximately 130 rules in the program.

To demonstrate the effectiveness of the proposed expert system, fault location identification has been performed on a distribution system within the service area of the Taipei City District Office of Taiwan Power Company. The study system comprises 5 primary feeders, 49 laterals and sublaterals, and 138 branching points. Among the customers served by the study system, there are 46 key customers.

The inputs to the expert system are the addresses of the customers out of service. The outputs of the expert system include the address of each device in the fault region and the connectivity of these devices. The case under study involves a fault event at branching point 17 of Fig. 5. There are two customers who reported service interruption in the case. Neither of the customers is a key customer. Fig. 5 shows the address of customer 1 and the associated candidate fault region generated by the expert system through dynamic searching and backtracing (see blocks 4 and 5 of Fig. 2). The address and the candidate fault region of customer 2 are shown in Fig. 6. Fig. 7 gives the intersection of these two candidate fault regions. It is observed from Fig. 7 that there are 3 branching points (#16, #17, and #20) and three cable sections (1–16, 16–17, and 17–20) within the potential fault region at the present stage. To use key customer information to further narrow down the fault region, the expert system finds out that there are two key customers who are supplied power from branching points 16 and 20, respectively, and prints out the telephone numbers and addresses of these key customers. After the user calls up the two customers, it is found that only key customer 20 is interrupted. After receiving this information from the user, the expert system concludes that the branching points 17 and 20 and cable sections 16–17 and 17–20 are the potential outaged devices. The results are depicted in Fig. 8. A group of troublemen must be dispatched to have a look at these devices in order to exactly locate and isolate the fault.

During the study period of this project (May 1989 through April 1990), 19 outage events were reported within the study system. All the outage events were analyzed by the expert system. Among them, 17 cases were successfully diagnosed.

5. CONCLUSIONS

In this paper, an expert system has been developed to serve as an operational aid for the dispatchers to locate the faults in a distribution system. Since the location, address and connectivity of each device have been stored in the database of the expert system, the dispatchers do not have to look up the feeder circuit configuration maps in the process of diagnosing the fault. The heuristic rules gained by experienced dispatchers from previous operational experience are imbedded in the rule base. These system data and heuristic rules form the bases for the deductive reasonings performed by the inference engine to locate the fault. The inference engine comprises three major algorithms: the dynamic searching method, the backtracing approach, and the set intersection operation. To facilitate the com-

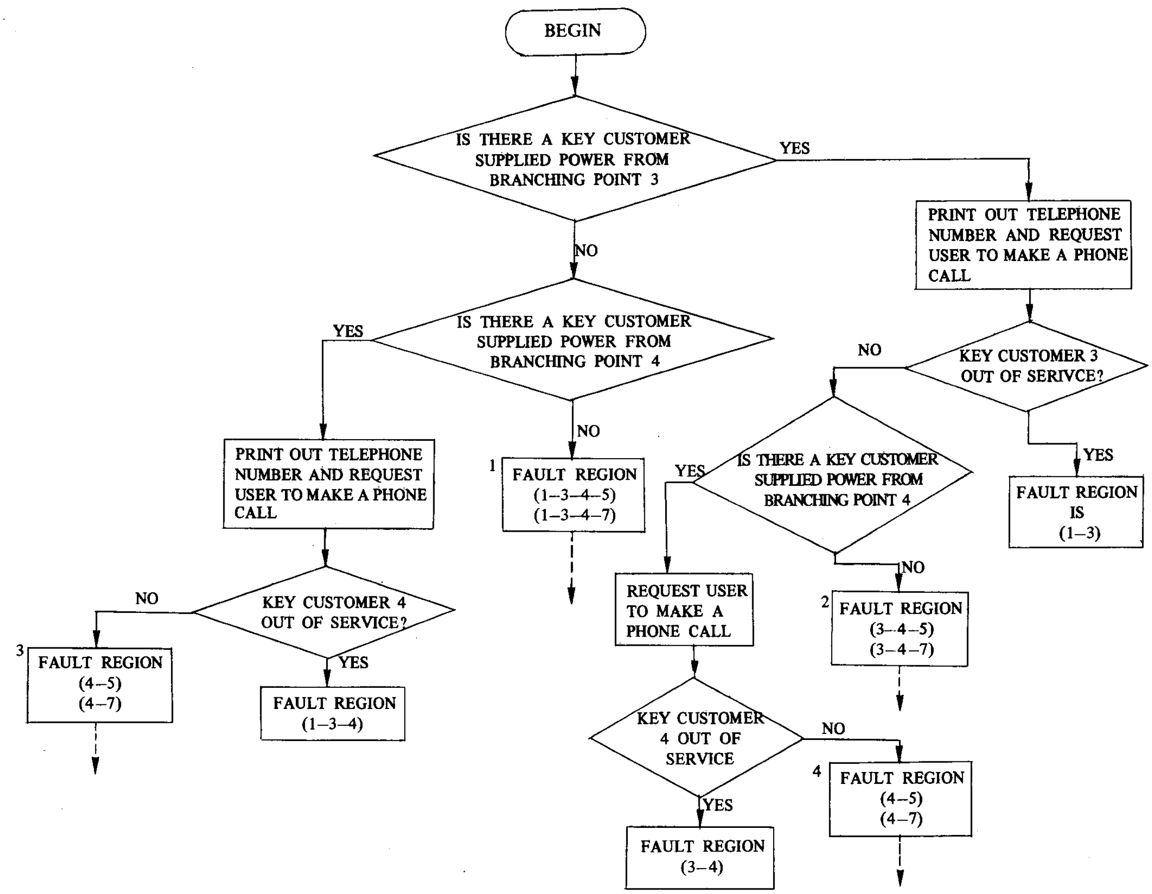


Fig. 4 Detailed procedures for narrowing down Region 1 and Region 2 in the example

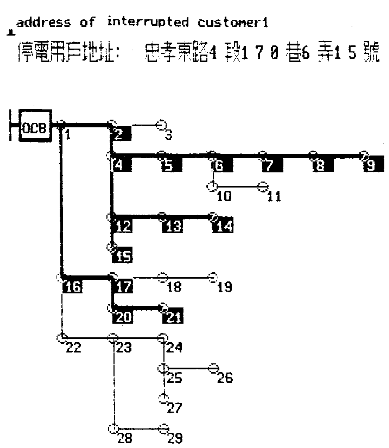


Fig. 5 Address and candidate fault region for customer 1

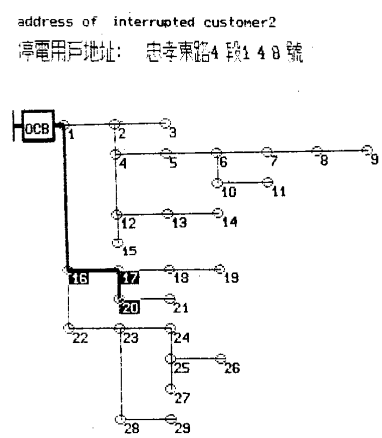
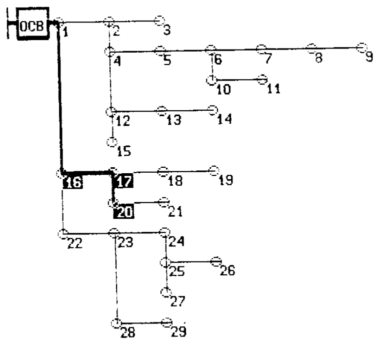


Fig. 6 Address and candidate fault region for customer 2

fault region after set intersection operation

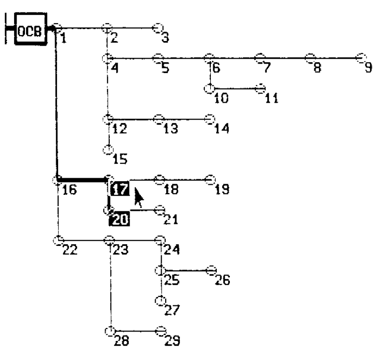
可能故障區域



branching point 配電室	telephone number 電話號碼	address 地址
16	(002)0572316	忠孝東路4段146號
17	---	忠孝東路4段142號
20	(002)0572512	忠孝東路4段170巷6弄3號

Fig. 7 Intersection of the two candidate fault regions

final result



branching point 配電室	address 地址	service interrupted? 是否停電
16	忠孝東路4段146號	no
17	忠孝東路4段142號	?
20	忠孝東路4段170巷6弄3號	yes

Fig. 8 The final results from the expert system

munication between the expert system and the user, a user-friendly Chinese input/output system is also designed. The effectiveness of the designed expert system is demonstrated by fault diagnosis on a distribution system within the service area of the Taipei City District Office of Taiwan Power Company. Our future effort will be devoted to expanding the database to cover the entire service area of the Taipei City District Office. In addition, the case of multiple fault events will also be studied in our future work. But additional meters may be required in this case.

6. ACKNOWLEDGMENTS

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Yuan-Yih Hsu was born in Taiwan on June 19, 1955. He received his B.Sc., M.Sc., and Ph.D. degrees, all in electrical engineering from National Taiwan University, Taipei, Taiwan.

Since 1977, he has been with National Taiwan University, where he is now a professor. He worked at the University of Calgary, Alberta, Canada, as a postdoctoral research fellow and instructor from 1982 to 1983. From 1988 to 1988, he was a visiting scholar at the University of California, Berkeley.

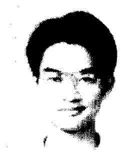
At present, his research interests include power system dynamics, stability analysis, reliability analysis and the application of expert systems to power system problems.

He is a senior member of IEEE.

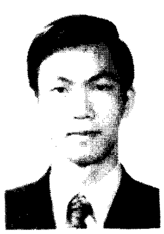
Lu Feng-Chang was born in Tainan, Taiwan on Dec. 1, 1961.

He received B.S. degree from National Taiwan Institute of Technology in 1988.

Before joining NTIT in 1986, he worked for two years as a design and planning engineer in Taiwan Power Company. His research interests include graph theory applications in power systems, power system operation, artificial intelligence and expert systems.



Chien-ye was born in Taipei, Taiwan on June 27, 1965. He received B.E. degree from Chung Yuan University in 1988. He is now a graduate student in National Taiwan University Taipei, Taiwan.



Liu, Jih-Phong was born in Taiwan, Taiwan, R.O.C., in 1947. He received the B.E. and M.S. degree in electrical engineering from National Cheng-Kung University, Tainan, Taiwan, in 1970 and 1973, respectively.

In 1973, he joined the Taiwan Power Company, working in the power system analysis. He later became the head of high power planning division of power research laboratory. At present, he is a manager of R&D planning office of Power Research Institute, TPC.

Lin, Jiann-Tyng was born in Tainan, Taiwan, R.O.C., on November 11, 1954. He received the B.E. and M.S. degree in electrical engineering from National Cheng-Kung University, Tainan, Taiwan, in 1977 and 1979, respectively.

He worked for the Taiwan Power Company as a planning engineer of high voltage and high power laboratory during 1981-1985. Since 1985, he has been working on R&D planning office, Power Research Institute, TPC, as a planning engineer of R&D projects.

Paul H.S. Yu was born in Taiwan, ROC, in 1931. After receiving the B. Sc. degree from National Taiwan University, he has been working on distribution system engineering for 33 years. Now, he is the manager of Taipei City District Office of Taiwan Power Company.

Robert R.T. Kuo was born in Taiwan, ROC, in 1942. After graduating from Taipei Institute of Technology, he has been with Taiwan Power Company for 25 years, working in the field of distribution system engineering. He is now Chief of Maintenance Division, Taipei City District Office, Taiwan Power Company.