An Advanced Fault Diagnosis System

Young-Moon Park, Bok-Shin Ahn, and Heung-Jae Lee

Abstract

This paper presents an advanced fault diagnosis expert system to assist the operators at local control centers. The system utilizes all the information available in a local control center for the better diagnostic performance. The major feature of the system is dealing with multiple faults diagnosis based on the certainty factor method for the reasoning process. The overall performance and the generality are also enhanced by utilizing the general topological knowledge. A SCADA simulator is also developed for the test and demonstration.

I. Introduction

During the last few decades, many expert systems have been proposed to deal with the fault diagnosis problem for substations or dispatching centers that are equipped with PC-based small scale SCADAs or large SCADA systems to assist the operators. Fukui[1] and other good papers[2, 3] have proposed the expert system approaches to diagnose the faults in a transmission network. On the substation side, Protopapas[4] proposed an interactive expert system using PC-based SCADA. Venkata[5] proposed a basic expert system installed in the ICPS (Integrated Control and Protection System). Japanese power companies also announced many prototypes or practical systems[6-9] for the unit substation. Kansai power company developed a system for a 500 kV[6] and a 275 kV substation[7]. Tokyo electric power company developed a supervisory system[8], and the Chubu power company presented a frame based expert system[9].

This paper presents a practical expert system for the fault diagnosis in multiple distribution substations including the transmission network. As many other countries, Korean power system has a hierarchical distributive control structure. One EMS in the top level covers 10 Regional Control Centers (RCC) and there are many Local Control Centers (LCC) as the subsidiaries of a RCC. The major roles of a LCC are to monitor and to control the affiliated distribution substations. The system proposed in this paper is the more advanced system than the previous one, which was installed as a part of the intelligent support system in a LCC, and has been tested until now. The major characteristics of this expert system are the fault diagnosis for multiple substations and multiple faults, facilitating uncertainty, and hypothesis generation (explanation function) with the discrimination between the false operation and non-operation of protective devices. Another special feature of the system is the utilization of a general topological knowledge base[10]. This feature leads to the compact and efficient structure as well as the enhancement of the performance of the integrated system.

In this paper, the structure of the integrated diagnosis system is introduced including the general topology-based knowledge and the certainty factor method for the uncertainty manipulation. Finally, the SCADA simulation system is introduced.

II. Defintion of the Problem Domain

A typical distribution substation in Korea consists of 2 to 4 transmission lines(TLs), double high voltage buses(HBUSes), 2 to 4 main transformers(MTRs) and a few of low voltage distribution buses(LBUSes) including many switches such as circuit breakers(CBs) and line switches(Lses). Besides, there are many kinds of protective relays. As mentioned before, these substations are almost unmanned in the urban area of Korea. About 8 to 12 regional substations are controlled by a local control center through the remote control.

When a fault occurs, the information of protective devices is transmitted to the minor SCADAs -- a smaller scale SCADAs -- than that in a RCC. Then, the operators scroll the alarm pages on a monitor as well as the graphic pages corresponding to the alarm set on the other monitors. As the next process, they infer the estimated fault section based on the alarm set and the graphic display. The reasons why they look at the CRTs are not only that the displays show the states of switching devices, but also that the black-out region can be identified easily on the GUI. Also, the fault sections clearly exist within the black-out

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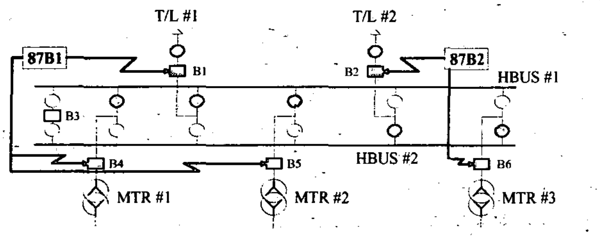
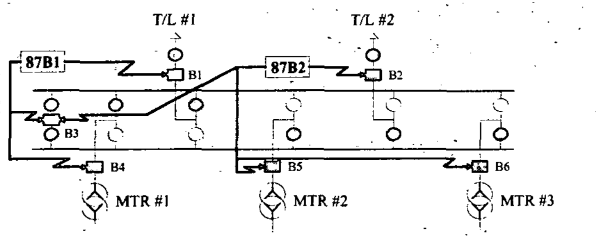
area. When a fault occurs inside a substation, and if the effect does not spread over contiguous substations by the proper operation of protective devices, then the diagnostic region is limited to the substation area. However, if the related protective devices would fail or malfunction, the transmission line protection system in adjacent substations will operate. Then the black-out area is enlarged. This problem requires the combined diagnosis of transmission lines and substations.

The tripping breakers corresponding to one protective relay are dependent on the states of other switches. The operator's inference is definitely based on this topological information, especially when the bus differential relay operated. Fig. 1 illustrates the situation.



(a) Case 1: T/L #1 supplies MTR #1, #2 and T/L 2 supplies MTR #3, Tie CB is off



(b) Case 2: T/L #1 supplies MTR #1 and T/L 2 supplies MTR #2 and #3, Tie-CB is on

REMARKS : ☐ CB on ☐ CB off ○ LS on ◌ LS off

Fig. 1. Variation of the tripping breakers due to the states of other switches.

Both Fig. 1-(a) and 1-(b) represent the states of CBs and LSes in the pre-fault stage. In Fig. 1-(a), if the bus-tie breaker is off and T/L #1 supplies electricity to the MTR #1 and #2, the bus differential relay #1 (87B1) will trip the breakers B1, B4 and B5 when a fault happens in the high voltage bus#1. In case of a fault in the bus#2, the relay 87B2 will trip B2 and B6. In Fig. 1-(b), the tripping breakers corresponding to the 87B1 will be B1, B4 and B3 -- the bus-tie breakers. The 87B2 will trip B2, B3, B5 and B6, either. These conversions are automatically set by the internal electro-mechanical interlocking system. Although the topology of this example is somewhat simple, there could be 64 different combinations of tripping breaker sets according to the states of switching devices. A larger substation may have 4 TLs and 4 MTRs. In the case, there could be 512 combinations based on the assumption that all transmission lines are active. Considering the reserved lines may generate more combinations.

As the operators are good at this mechanism, they are looking at the monitor and think the causal relationship instinctively based on his topological knowledge. In fact, his implicit knowledge is simple in a linguistic form such that *if a fault occurs in a bus #N (N=1, 2), the differential relay will trip the breakers that are connected to the bus #N.* Therefore, how to interpret the linguistic terms using an AI language is the main issue. It is well known that the number of rules is important to enhance the performance of an expert system. But it should be noted that as one rule consists of several terms including the facts in the knowledge base, the definitions and data structure of the terms and facts also play important roles in realizing the general human knowledge that will enhance the performance and generality of the system eventually. Furthermore, as the terms are not only a part of rules but also the basic target in the searching process by the unification, the definition and data structure should be taken care of.

III. Structure of the Diagnosis System

The overall structure of the intelligent system is illustrated in Fig. 2. It is composed of a meta-inference system and the three expert systems.

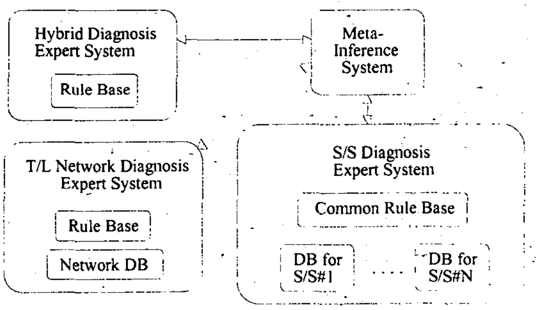


Fig. 2. Structure of the intelligent system.

Each expert system is composed of its inference engine, rule-base and static database which has time-independent data. And the systems also share common real-time database that contains instantaneous states or alarms delivered from the remote terminal units through SCADA.

Database

The basic information on the unit devices and protective relays as well as the alarms are included in the database. Besides, there are additional analog data such as real/reactive power, voltage and current at each point, which are monitored periodically by the SCADA system. Although this information does not indicate the fault section directly(there could be a controlled operation), the information is used in this system to verify the diagnostic results.

Rule-Base

Many rules are stored in the rule-base and they are classified into the following categories.

1. Rules to define the topological terms [10]
2. Rules to find the actual connection path [10]
3. Rules to find the fault propagation
4. Operating rules of the protective devices
5. Rules to discriminate the false operation and/or the non-operation of the protective devices
6. Heuristic rules
7. Rules for the fault section estimation
8. Rules to generate the hypothesis and the report

As these rules are represented using the general terms, they can be applied to all the substations in the LCC regardless of the number of transmission lines, transformers, distribution buses and distribution lines. It means that the number of rules is independent of the number of elements in each substation. This feature is similar to that of the human experts. In practice, over 300 PROLOG style rules have been developed at first, and they were translated into the C-language for the effective links with the main program and the other expert subsystems.

Ⅳ. Certainty Factor Method

When a fault occurs in an element, the corresponding protective relays will operate usually. Then each relay will trip one or multiple circuit breakers. Since the active relays and tripped circuit breakers cause the alarms, it is obvious that the cause of a breaker's trip is a relay, and the relay operation is caused by a fault. But in case of the non-operation or the false operation, the situation will be complicated. In this paper, a false operation means the operation of a device by disturbances or malfunctions without any proper cause. In the real system, only the result part is known in the form of the alarms with the pre-fault and post-fault states of the devices. In the multiple faults case, the problem becomes more complex. As there are many possible solutions, even in the case of single fault, inexact reasoning is indispensable in nature. The certainty factor method [11] was applied for the simple manipulation. The certainty factor(CF) approach, originally used in the well-known 'MYCIN' system, is based on Buchanan's confirmation theory and it has been refined through several modifications. The proposed expert system uses the modified formulation, which is used in EMYCIN, a general expert system shell. Brief summary on the certainty factor is as follows.

The certainty *CF(h, e)* factor of a given hypothesis '*h*' is defined as the difference between a measure of belief *MB(h, e)* representing the degree of support of a evidence '*e*' and a measure of disbelief *MD(h, e)* representing the degree of reputation of the evidence. The measures of belief and disbelief could be interpreted as a relative distance on a bounded interval and the *CH* means the degree of confirmation. These have the following forms:

$$MB(h, e) = \begin{cases} \dfrac{P(h, e) - P(h)}{1 - P(h)} & \text{if } P(h, e) > P(h) \\ 0 & \text{otherwise} \end{cases}$$

and

$$MB(h, e) = \begin{cases} \dfrac{P(h, e) - P(h)}{1 - P(h)} & \text{if } P(h, e) < P(h) \\ 0 & \text{otherwise} \end{cases}$$

In the above expression, some counter-intuitive behavior was detected. The definition of the *CF* can be modified as follows;

$$CF(h, e) = \frac{MB(h, e) - MD(h, e)}{1 - \min(MB(h, e), MD(h, e))} \tag{1}$$

which was used in EMYCIN and is also adopted in this expert system.

With some combination operations, the following propagation equation;

$$CF \text{ combine } (x, y) = \begin{cases} x + y - xy & \text{for } x > 0, y > 0 \\ \dfrac{x = y}{1 - \min(x, y)} & \text{for } xy < 0 \\ x + y - x & \text{for } x < 0, y < 0 \end{cases} \tag{2}$$

and in the case of conjunction, fuzzy operator is used as follows:

$$CF(x\ y) = \min(CF(x), CF(b)) \tag{3}$$

Fig. 3 illustrates an example which shows the paradigm of the fault diagnosis in this system.

Example

If it is assumed that the fault occurred only at the HBUS #1 in Fig. 3, the following hypothesis is a reasonable inference result.

Possible solution #1.

Fault occurred at the HBUS #1.
87B1 failed.
Z2 of Substation A operated to trip B11.
Z2 of Substation B operated to trip B21.

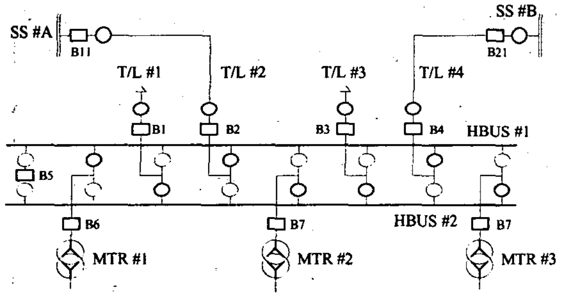
Using the similar inference procedure, evidently two more probable solutions are possible.

Possible solution #2.

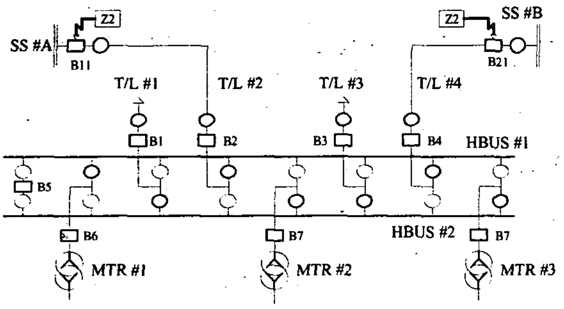
Fault occurred at the TL #2.
Z1, Z2 of Substation C failed.
Z1 of Substation A failed.
Z2 of Substation A operated to trip B11.
Z2 of Substation B operated to trip B21.

Possible solution #3.

Fault occurred at the TL #4.
Z1, Z2 of Substation C failed.
Z1 of Substation B failed.
Z2 of Substation A operated to trip B11.
Z2 of Substation B operated to trip B21.



(a) Pre- fault condition of a sample substation



(b) Post-fault condition of a sample substation

REMARKS : ☐ CB on ☐ CB off ○ LS on ◌ LS off

Fig. 3. Example of the fault diagnosis.

Table 1. Possible Solutions.

No.	Fault assumption	Non-operation	False operation
1	HBUS #1	87B1	None
2	TL #2	87B1	None
3	TL #4	87B1	None
4	HBUS #1 & TL#2	87B1,Z1,Z2	None
5	HBUS #1 & TL#4	87B1,Z1,Z2	None
6	TL#2 & TL#4	Z1,Z2	None
7	No fault	None	Z2

These three solutions are based on the single fault assumption. In fact, there are many solutions as shown in Table 1.

As it was pointed out, the discrimination between the non-operation and the false operation is generally possible only with the assumption of the fault section.

The certainty of non-operation and false operation for each device was carefully assigned through the analysis of the fault history in the KEPCO system. Briefly speaking, the certainty order was assigned as follows:

CF(non-operation of a CB)
> *CF*(non-operation of a relay)
> *CF*(false-operation of a relay)
> *CF*(simultaneous multiple faults),
where represents the certainty.

Considering the certainty order, the system generates seven solutions in this example. In Table 1, it is obvious that the solutions No. 2 and No. 3 have equal possibilities provided that the time information is not considered. Although the time information is available by the SOE (Sequence Of Event) option in the most SCADA systems, it is disabled usually in the KEPCO system. If it is available and it is the perfect information, then one of the two solutions will be meaningless. The proposed system does not utilize the time information for now.

V. Flow Chart of the Process

At a normal state, the main expert system monitors the states of switching devices and updates the topology data if some changes are detected from the periodically scanned data from SCADA. When an alarm set is received from SCADA due to the faults, pre-processing is required because each of the original alarms is only a few bytes of digital codes. The main system converts the codes into the linguistic predicates. In the next step, the main system saves the previous states of the devices as a pre-fault data, updates the topology, and calls the diagnosis system. In this step, the fault diagnosis system generates the possible solutions one by one. The backward reasoning method is used. The third step is the ordering process based on the possibility of each solution. For the generation of the hypotheses, dynamic database is chosen. Finally, when the report is generated, the main system calls the restoration plan generation expert system with the estimated fault sections. Fig. 4 shows the overall flow chart of the system. Each step consists of one sub-goal in the system and the inexact reasoning process is activated at the priority ordering and report generation stages

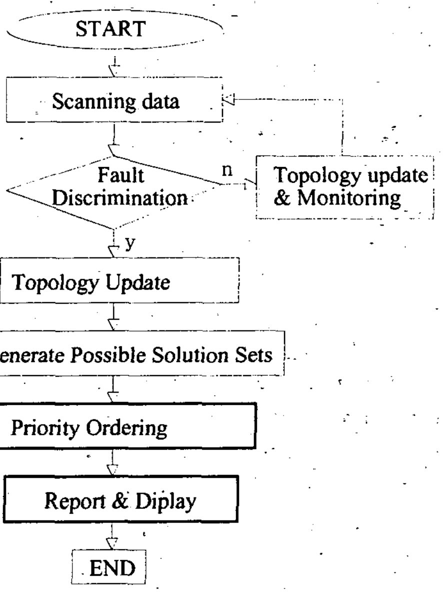


Fig. 4. Flow chart of the fault diagnosis.

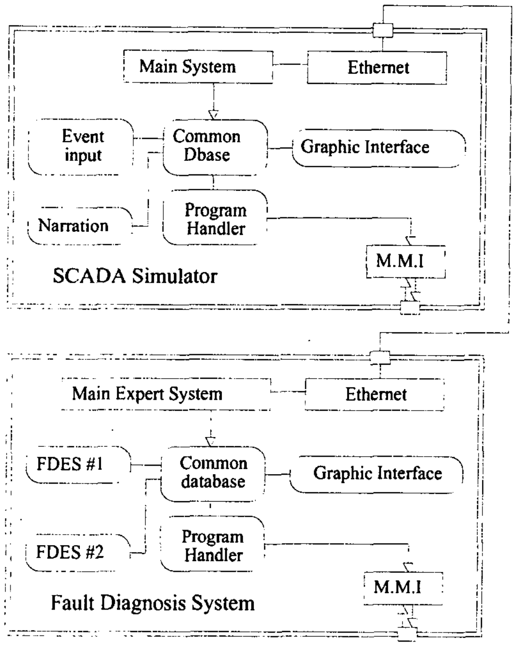


Fig. 5. Overall structure of the test system.

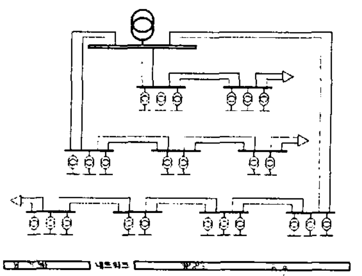


Fig. 6. Display #1 - total network.

Ⅵ. Structure of the Test System

The overall structure of the test system is shown in Fig. 5. The intelligent system consists of a main expert system for meta-inference including the graphic user interface, and 2 subsidiary expert systems as explained before -- a fault diagnosis expert system for substations and a fault diagnosis expert system for transmission systems. This system is connected to the SCADA simulation system (SIMSCADA) by the Ethernet LAN subsystem.

The major features of the SIMSCADA are the event generation function to emulate the front-end processor for RTUs, a multimedia guidance system and the graphic interface system. Fig. 6 and 7 show the graphic displays of the SIMSCADA. Fig. 6 is the screen display of a sample network that consists of 9 substations and transmission lines. Fig. 7 shows the display of the internal states of switches in a specified substation.

The previous version of this system was applied as a part of the intelligent support system to assist the SCADA operators, which was installed in the Ui-Jung-Bu local control center nearby the capital Seoul in 1994 and has been tested up to now. The intelligent system is still in the progress. Many functions will be added eventually.

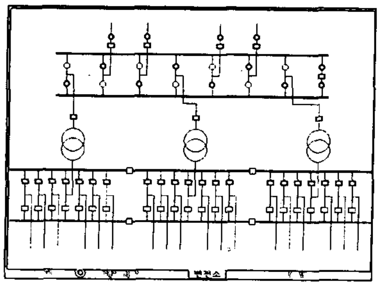


Fig. 7. Display #2 - a substation.

Ⅶ. Conclusions

An advanced on-line fault diagnosis system was developed to assist the SCADA operators. The system is able to diagnose the various faults in the local transmission network including the subsidiary substations through the inexact reasoning process. A general representation method for topological modules was proposed. And the discrimination of false and non-operation as well as dealing with the multiple faults was also discussed in detail.

Since the original system, which has been tested in a local control center of Korea as a part of the intelligent support system, is lack of multiple faults diagnosis function, it is being updated continuously. The system is able to diagnose any kind of faults within one second even in the worst case. Case studies including the mixed fault problems using the historical data proved the 100% diagnostic performance of the system, which means that the real fault sections have been exactly estimated by the most possible solution for all cases.

Acknowledgement

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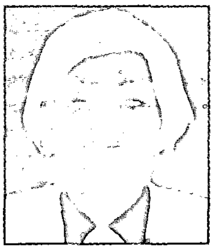

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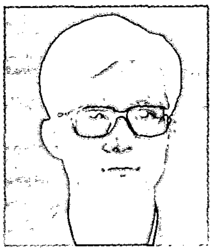

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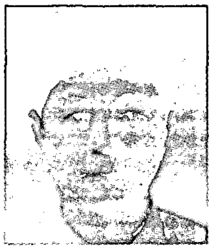

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