Fault Diagnosis of Power Systems

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Invited Paper

Fault diagnosis of power systems plays a crucial role in power system monitoring and control that ensures stable supply of electrical power to consumers. In the case of multiple faults or incorrect operation of protective devices, fault diagnosis requires judgment of complex conditions at various levels. For this reason, research into application of knowledge-based systems got an early start and reports of such systems have appeared in many papers. In this paper, these systems are classified by the method of inference utilized in the knowledge-based systems for fault diagnosis of power systems. The characteristics of each class and corresponding issues as well as the state-of-the-art techniques for improving their performance are presented. Additional topics covered are user interfaces, interfaces with energy management systems (EMS's), and expert system development tools for fault diagnosis. Results and evaluation of actual operation in the field are also discussed. Knowledge-based fault diagnosis of power systems will continue to disseminate.

I. Introduction

Fault diagnosis of power systems involves identifying the location and cause of faults occurring in the power system due to lightning strokes, and so on. The systems that implement these functions represent the most practical application of knowledge-based systems in the power system field.

In this paper, the accomplishments and limitations of the diagnostic techniques for power systems are discussed. In Section II, the effectiveness of knowledge processing in fault diagnosis of power systems is discussed. In Section III, the methods of fault diagnosis of power systems applied to transmission networks are classified and an overview, characteristics and issues for each approach are presented. The methods utilized to improve performance, which is currently the most important issue in fault diagnosis, are discussed from the hardware and software viewpoints in Section IV. In Section V, the user interface, the interface with energy management systems (EMS's) and expert system development tools for fault diagnosis as they relate to the knowledge-based architecture of fault diagnosis systems are discussed. Finally, other functions related to fault diagnosis are introduced in Section VI.

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II. Fault Diagnosis of Power Systems

A. The Necessity of Fault Diagnosis

The ultimate purpose of a power system is to transport electrical power from the power generation station to the consumer. As a result, it is configured from transmission and substation facilities distributed over a large geographical area. In order to achieve stable supply of electrical power, the power system must be extremely reliable. It is inevitable, however, that accidents such as lightning strokes, collisions with transmission lines, and failures due to aging equipment and random failures will occur. When a fault due to these causes does occur, it is imperative to limit the impact of outages to the minimum and to restore the faulted facilities as quickly as possible. This requires that the location and nature of the fault first be identified. This identification function is referred to as "fault diagnosis of power systems." This fault diagnosis function is then the most basic fault handling function of power system supervisory and control systems such as EMS and supervisory control and data acquisition (SCADA) systems.

Fault diagnosis can be divided into local fault diagnosis and centralized fault diagnosis. Local fault diagnosis takes place at power plant and substation facilities and aims to diagnose these facilities. Centralized fault diagnosis takes place at control centers equipped with EMS and SCADA systems using transmitted fault information. This paper is primarily concerned with centralized fault diagnosis.

B. Application of Knowledge-Based Systems

In conventional systems, fault diagnosis is performed using a table of possible faults that contains information concerning operating protective relays, tripped circuit breakers, fault location, and fault type that is prepared in advance. When a fault occurs in the power system, this

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table is referred to in order to identify the location and type of fault.

This approach correctly diagnoses the case of a simple fault like a single fault with correct operation of protective relays and circuit breakers. However, in the case of a single fault complicated by unwanted operation of protective relays and circuit breakers or simultaneous multiple faults as often occur in the case of lightning strokes, the processing becomes excessively complex and the diagnosis is not always correct.

When unwanted operation of devices and multiple faults are reflected in the fault diagnosis, the correct diagnosis can be obtained by performing various intersections of relay's protection zones and other conditions. If, in addition, installation of protective relays and sensors is inadequate, or the effects of weather and damage by animals are to be considered, knowledge based on experience becomes essential. If special relays are installed, or the power system is operated in a special network configuration, special processing may also be required.

It seems that realizing a fault diagnosis system via a knowledge-based system is appropriate under the above conditions. As a result, research into knowledge-based fault diagnosis systems got a relatively early start. There are already several systems in actual operation.

III. Methods of Fault Diagnosis

A. Classification of Fault Diagnosis Methods

Previously reported knowledge-based systems for fault diagnosis include those shown in Table 1. Each of these systems uses one of two approaches. The first approach consists of organizing monitoring information from operating relays and tripped circuit breakers during a fault and its relationship to fault conditions into a tree structure or in tabular form. This is referred to as the monitoring information-based approach. In the other approach, the structure and functions of the protective relaying system are modeled, the fault conditions are simulated and diagnosis is made comparing the simulation results with the actual monitoring information. This is referred to as the model-based approach. An overview of each approach and their characteristics are presented in the following sections.

The accuracy of fault diagnosis is greatly affected by the type of on-line data from the power system used in the diagnosis. It is desirable to input the tripped circuit breakers and every type of relay that trips the circuit breakers. Ideally, this input data should also be time-stamped. However, the relay information actually input is generally much less. It is common for only main protection/backup protection and short-circuit/ground fault information to be input. There are also cases of only short-circuit/ground fault information being input [6], [20].

B. Monitoring Information-Based Approach

1) Overview: In the early systems such as [1], the knowledge base was closely tied to a particular network configuration and was thus fixed. In actual operation this proved problematic since the systems could not adequately cope with changes in the network configuration. Several systems including [2]–[10], [11] were subsequently developed to resolve this problem. The algorithms that are used in these systems can largely be divided into two types. In the first type, a method used in early systems that did not apply a knowledge-based system was employed. The fault is diagnosed in three steps, proceeding from cases where all operating relays and circuit breakers operate properly, to cases of incorrect nonoperation and then unwanted operation [21], [22]. In later systems knowledge-based systems were applied to improve the efficiency of detection of incorrect nonoperating and unwanted operating relays and circuit breakers using experience rules [3]–[5]. In addition, systems that perform verification by using the results of the first method as the input to a protective relay system simulator were developed [6], [7], [11].

In the second type, the fault location is diagnosed by judging the incorrect nonoperation and unwanted operation of relays and circuit breakers using the intersection set of the protection zones of operating relays. If there is only one element in the intersection set, it is judged that element is faulted. If there are two or more elements in the intersection set, the fault is located at element, but it is impossible to make further identification. If the intersection results in an empty set, the operating relays are divided into two groups and the intersection is repeated in order to allow for a multiple fault. Finally, fault diagnosis using knowledge in the form of experience rules to deal with unusual fault cases such as blind faults that involve relay characteristics is performed.

2) Characteristics: In order to obtain a high-speed algorithm in the monitoring information-based approach, not all of the relaying system's complex functions are taken into consideration. One example of this simplification is setting the protection zone of the protective relay equal to the set of protected equipment.

All of the systems [3]–[5], [8]–[10] at the field testing stage utilize this approach. It has been indicated that this approach allows configuration of a practical system for the preparation of fault restoration guidelines.

3) Topics for the Future: Concerning complex functions of protective relays, the monitoring information-based approach considered here only allows for special processing of faults that have been experienced. In the case of occurrence of faults that have not been experienced, the diagnosis may be incorrect.

In order to reduce the number of cases that cannot be correctly diagnosed, a huge amount of knowledge for special processing must be prepared. As a result, the following issues need to be investigated.

1) Since fault diagnosis knowledge must be prepared for the large amount of monitoring information required to improve diagnosis capabilities, an efficient method of extracting such knowledge from operators must be developed.
2) The operating sequence of the relaying system is not incorporated into the rules relating monitoring

Table 1 Knowledge-Based Fault Diagnosis Systems

	Ref.	Languages, tools	Fault diagnosis accuracy*	Characteristics
Monitoring information-based methods	[1]	Prolog/KR	Apparatus	Knowledge base is dependent on network config.
	[2]	LONLI (Prolog)	Relay protection zone/fault location	Allows for changes in relay protection zone due to circuit breaker status.
	[3], [4], [5]	Prolog, TDES3	Relay protection zone/fault location	Stratified expert diagnosis knowledge is applied layer by layer.
	[6], [7]	OPS5	Apparatus	Implemented in distributed control system via black-board model.
	[8], [9]	Fortran, EUREKA II	Relay protection zone/fault location	Table of relay op. and corr. faults is created from relay operation scenario.
	[10]	OPS83, C	Apparatus	Basic algorithm plus experience knowledge for unusual faults.
	[11]	ESHELL/X	Relay protection zone/fault location	Relay characteristic is represented by protection zone and time setting.
Model-based methods	[12], [13]	ZetaLisp	Apparatus	Protective relay sequence converted into logic circuit and logic circuit diagnostics applied.
	[14]	–	Apparatus	Proposed diagnosis method using simulation.
	[15]	OPS5, Lisp, C	Apparatus	Formulated as set cover problem and solved with hybrid knowledge/algorithm approach.
	[16]	Production system	Relay protection zone/fault location	Flow of fault current is simulated. Unusual faults can also be diagnosed.
	[17], [18], [19]	Lisp	Relay protection zone/fault location	Hypothesis of fault conditions created from model, diagnosis by simulation.

*Fault diagnosis accuracy refers to the smallest unit that can be identified in fault diagnosis.

information and fault conditions. Thus a method must be developed to verify the diagnosed result.

3) Faults ranging from commonplace to extremely unusual are included in the rules relating monitoring information and fault conditions. A method is needed for verifying whether fault conditions of all faults with over a certain percentage of possible occurrence or over a certain level of seriousness are actually contained in the knowledge base.

C. Model-based Approach

1) Overview: In the model-based approach, a number of proposals have been made that differ in the manner of expressing the model. One effort has been directed at expressing the protective relaying system configuration and functions as an AND–OR logic circuit, and using logic circuit diagnostics to perform fault diagnosis [12], [13]. However, not all of the protective relaying system's functions can be converted into AND–OR logic circuits. Since it is necessary to completely express the operating logic of the protective relaying system in logical format, some technique must be developed to simplify the representation for application to large-scale power systems.

Several systems have been proposed that utilize simulators of the protective relaying system as the model [14]–[16]. The basic approach to utilizing a simulator for fault diagnosis is proposed in [14]. Several other simulators of protective relaying systems have since been proposed.

In fault diagnosis utilizing simulation, a hypothesis as to the fault conditions is prepared from the monitoring information and the hypothesis is then verified via simulation. If the results of simulation match the monitoring information, the hypothesis is then judged as the solution of fault diagnosis. If the simulation results do not match the monitoring information, a new hypothesis with revised fault conditions is generated. Fault diagnosis is completed when all hypotheses have been simulated.

In this method it is necessary to prepare knowledge for generation and revisions of fault condition hypotheses in addition to the simulation. In order to perform correct fault diagnosis, there must be a good correspondence between the level of simulator functions and the knowledge used to perform generation and revisions of the fault condition hypotheses. Obtaining this correspondence involves implementing complex functions in the simulator in order to increase the accuracy of fault diagnosis, which is expected to be fairly problematic.

For this reason, a method of using general-purpose procedures to process the model, instead of knowledge contained in the object system to generate and revise fault condition hypotheses, has been proposed [17]–[19], [23]. According to [19], since the fault diagnosis system can be implemented just by creating a model, the validity of fault diagnosis results resides solely in the model. As a result, one benefit of the system is that the performance of the system can be easily evaluated by verifying the accuracy of the model.

2) Characteristics: In contrast to the monitoring information-based approach, use of a model-based simulator allows complex protective relaying system functions to be implemented relatively easily. In the monitoring information-based approach, the monitoring information is directly processed in order to obtain a fault diagnosis solution and consideration of complex functions requires a lot of special processing. In contrast, when a simulator is used there is a possibility that the knowledge used to generate and revise the fault condition hypothesis can select a hypothesis that can explain the monitoring information, which is relativelysimple.

Another difficulty in using the monitoring information occurs when the information has been summarized or is only partially available [24], [25], [20]. This requires that the correspondence between the monitoring information and the fault conditions must be rethought of as a system. In the case of a simulator, fault diagnosis matching the level of available information can be performed by merely modifying the data transmission network model contained within the simulator.

3) Topics for the Future: In comparison to the monitoring information-based approach, the model-based approach tends to require more processing time since the fault conditions are simulated by a simulator. In addition, if the accuracy of the prepared model is not sufficient and actually occurring fault conditions cannot be simulated, incorrect fault diagnosis results may be generated. As a result, the following issues need to be investigated.

1) Investigation of a model representation and simulation policy that will provide higher speed processing.
2) Establishment of a method for determining the level of model accuracy to provide the required fault diagnosis performance [26].

IV. High-Speed Processing Techniques and Performance

Among the fault diagnosis functions, identification of the faulted network section for network restoration requires high-speed processing in order to guarantee stable supply of power to consumers. The inference result must be available in less than 1 min, and preferably in less than 30 s. However, the reality is that many systems cannot achieve this performance. As accuracy of determination of the faulted section is increased, the volume of knowledge must also be increased, which decreases processing performance.

The following expedients for increasing processing speed to resolve this problem have been proposed for knowledge-based fault diagnosis systems:

1) dedicated processor for inference processing;
2) parallel inference processing;
3) faster inference algorithms.

Each of these will be introduced.

A. Dedicated Processor

Processing performance and integration with conventional EMS and SCADA systems are important for expert systems that are designed to support fault diagnosis of power systems. A back-end processor for fault diagnosis that copes with these problems has been reported [4].

The configuration of a process control computer with a dedicated back-end processor and system functions distributed between the process control computer and the dedicated back-end processor is indicated in Fig. 1.

The dedicated processor only executes fault diagnosis processing. It communicates with the process computer via an internal bus which allows high-speed data transmission. A console connected to the internal bus is a workstation for development and maintenance of a knowledge base. The process control computer maintains a power system equipment data base, inputs power system status information, detects changes in the power system status, and performs alarm processing, network operation processing and output, user–interface processing, and other EMS and SCADA functions. It also activates the inference engine of the dedicated processor.

The specifications of the dedicated processor are given in Table 2. The processor is based on reduced instruction set computer (RISC) architecture with important modifications and extensions such as writable control storage and tag/exception handling hardware for faster execution of programs written in artificial intelligence languages.

The dedicated processor can execute the fault diagnosis function at high speed and the overall execution time

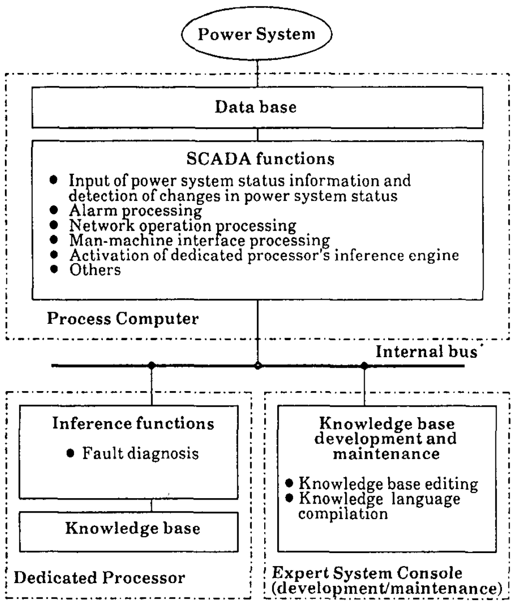

Fig. 1. Configuration of a system with functions distributed between a process computer and dedicated processor.

is only slightly affected by data transmission overhead. Typical performance of the fault diagnosis function with and without the dedicated back-end processor is indicated in Table 3. The dedicated processor and process control architecture shows a sevenfold improvement over the process computer alone. The data transmission overhead is small in comparison.

B. Parallel Processing and the Cause–Effect Network

Parallel processing is a useful means for reducing fault diagnosis processing time. References [27]–[29] deal with a cause–effect network-based knowledge representation, which is well suited to parallel processing.

1) Cause–Effect Networks: A cause–effect network represents the functions of protective relays and circuit breakers. The cause–effect network is composed of nodes and directed arcs which represent events and causality between events, respectively. A cause–effect network for fault diagnosis of power systems can be expressed with only three kinds of nodes and arcs, including the following:

2) (n1) Fault Section Node: The fault section node represents that section of a power system network which is affected by a fault. It is labeled with the name of the section.

3) (n2) Relay Node: The fault relay node indicates the action of a protective relay. It is labeled with the name of the protective relay.

4) (a1) Protected-by Arc: The protected-by arc, represented by

$$A \xrightarrow[\text{protected by}]{} B$$

indicates that a fault of section A causes the protective action of main protection relay B.

Table 2 General Specifications of Dedicated Processor

Item	Specification
Processor	32-bit processor based on RISC[1] and WCS[2]
Main memory	Min.: 32 MB Max.: 128 MB
Instruction set	Gen. RISC instructions: 100 Prolog: 45 LISP: 60
Performance	600K-LIPS

Notes: [1]Reduced instruction set computer.
[2]Writable control storage.

Table 3 Typical Performance of Process Computer and Dedicated Processor

System	Tasks				
	Data acquisition	Data transmission	Inference	Inference result transmission	Total
Process computer only	3 s (PC)	0 s	130 s (PC)	0 s	135 s
Process computer + Dedicated processor	3 s (PC)	0.2 s	15 s (DP)	0.2 s	20.4 s

DP: Processing time required for dedicated processor.
DC: Processing time required for process computer.

5) (a2) Cause Arc: The cause arc, represented by

$$A \xrightarrow[\text{cause}]{} B$$

indicates that the protective action of main protection relay A causes circuit breaker B to trip.

Figure 2 indicates a model power system. Figure 3 shows a cause–effect network that corresponds to the model power system indicated in Fig. 2. Suppose that a fault occurs along transmission line L, which causes protective action of main protection relays MR1 and MR2. MR1 and MR2 in turn transmit trip signals to circuit breakers CB1 and CB2, respectively. If relay MR1 fails to trip circuit breaker CB1, then backup relay BR1 is actuated to trip CB1.

6) Inference Procedures: Reference [28] describes a faulted section diagnosis method that utilizes information from protective relays and circuit breakers. This inference procedure involves the following phases: 1) generation of fault section candidates; 2) state estimation of circuit breakers; 3) estimation of incorrect system reactions; 4) estimation of multiple faults; and 5) selection of faulted section. These

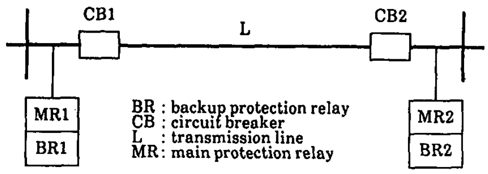

Fig. 2. Model power system.

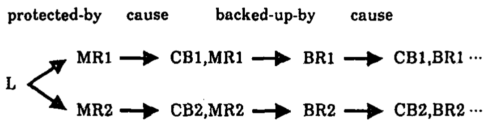

Fig. 3. Cause–effect network representation of model power system. BR: backup protection relay, CB: circuit breaker, L: transmission line, and MR: main protection relay.

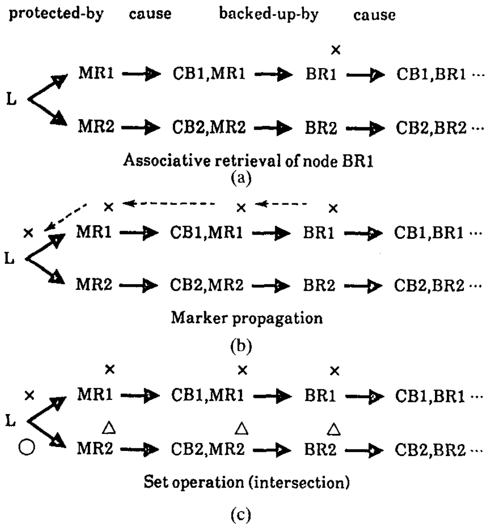

Fig. 4. Three kinds of operations in the cause–effect network. BR: backup protection relay, CB: circuit breaker, L: transmission line, and MR: main protection relay.

procedures are compiled into the following three simple operations.

1) *Associative retrieval*: Look up the node with a given name in the cause–effect network and set a marker there. For example, Fig. 4(a) shows the result of associative retrieval of relay BR1. The node representing relay BR1 is retrieved and marker × is placed there.
2) *Marker propagation*: Transmit each marker through arcs in a given direction. Figure 4(b) shows the result of marker propagation. The marker × is transmitted through arcs in the opposite direction to that of the arrows in the figure.
3) *Set operation*: Perform intersection of sets of markers in the network diagrams. Figure 4(c) shows an example of set operation, the intersection of a set comprising the nodes with marker × and another set comprising the nodes with marker △. The solution of this operation, say node L, is marked by marker ○.

7) Parallel Processing: The above operations can be executed efficiently in parallel. If each node in the cause–effect network is allocated to individual simple processors called processing elements, set operations and associative retrieval will be executed within a fixed amount of time, irrespectively of the size of the cause–effect network. The processing element is provided with a memory device of sufficient capacity to store the relevant information to allow operation within each node to be processed independently. Additionally, any number of nodes can then transmit markers simultaneously.

A machine for parallel processing of a cause–effect network must comprise a sufficient number of processing elements required to perform processing in parallel, and the processing elements must be interconnectable via software. Several so-called marker propagation machines that satisfy these requirements already exist [30]–[32].

8) Inference Speed: The inference speed of a cause–effect network is compared to a conventional rule-based system in paper [27]. Figure 5 shows the inference speed for some simple faults. The performance of the conventional rule-based system suddenly degrades when the number of operating relays exceeds three. In the case of the cause–effect network, the decrease in performance is at most only linear with an increasing number of operating relays. The performance of the cause–effect network is remarkable at all levels.

9) Time Sequence Information: In some cases, time sequence information may be available or soon available. Reference [29] deals with an expert system utilizing such information. The system makes use of operating times of protective relays and tripping time of circuit breakers so that the system can properly diagnose even multiple faults, and generate far fewer fault section candidates for faster inference speed.

V. Implementation

In this section, the authors focus on the implementation topics of expert systems for fault diagnosis.

Unlike prototype systems, the implementation technique is quite important in building expert systems that are actually used in the field. Implementation problems concerning expert systems and their resolution is discussed and actual implementation examples are presented [9], [4].

A. Interfacing with Energy Management Systems

Expert systems for the fault diagnosis of power systems are used in a real-time environment. On-line power system information such as prefault states and emergency states after faults is essential to the inference process.

Many computerized control systems such as EMS and SCADA systems are installed in power systems. Standard EMS functions include monitoring, operation control, recording, etc. Typical EMS's collect on-line data such as

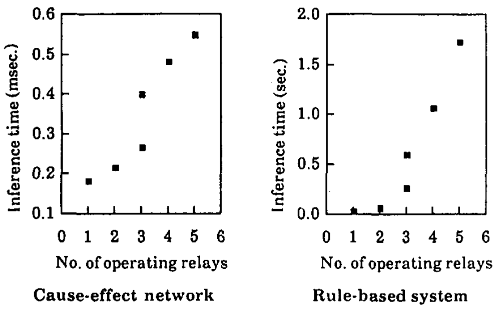

Fig. 5. Comparison of inference times between conventional rule-based system and cause–effect network.

supervisory control data and telemetry data from telecontrol equipment installed at substations and switching yards.

The aim of development of expert systems for fault diagnosis is to enhance these EMS functions. Therefore, in building the expert system, the interface with the EMS system via which the required data for fault diagnosis is obtained must first be considered. This raises two important issues:

1) burden placed on CPU power of EMS;
2) data transmission from the on-line database.

When a fault occurs, the CPU load factor of the primary EMS system jumps to a high level as alarm processing and recording is performed. Ideally, the expert system should not place an additional burden on the EMS functions. Concerning data transmission, the issue is the amount of time required to send data from the on-line database of the EMS to the knowledge base of the expert system. Two expert system implementations that deal with these issues are introduced.

1) Tightly Coupled System: One example of a tightly coupled system is the expert system that features a back-end processor integrated with the primary EMS system CPU via internal busses [4]. The configuration of this expert system that is installed at an integrated control center is indicated in Fig. 6. In this system, a dedicated processor is connected to process computers via an internal bus. Standard processes such as supervision or security monitoring can invoke the inference engine through a special interface.

One merit of this built-in architecture is efficient data transmission from the primary EMS data base to the inference engine.

2) Loosely-Coupled System: Another type of architecture is a distributed system with loosely coupled expert system. Figure 7 indicates the system configuration of such an expert system for the 500-kV substation operation guidance system [9], [33].

In this configuration, the processors for the expert system are separate from the main EMS system. Static data such as network configuration and apparatus data is downloaded in advance. When a fault occurs, the data for the changed state is transmitted via a local area network (LAN), and the inference process is invoked. The user interface processing

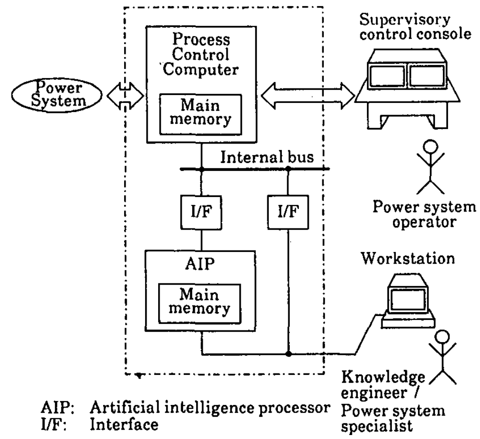

Fig. 6. Configuration of a tightly-coupled system for fault diagnosis.

is also executed by this CPU where the inference engine is located. This architecture allows the CPU's to share the processing load and the CPU of the EMS system is not impacted.

3) User Interface: The expert system for fault diagnosis is considered part of the guidance system of the EMS system as it assists human operators in recognizing the network condition after faults. The user interface is thus important.

The fundamental functions of this expert system are to determine when and where a fault has occurred, the type of fault and the area in outage. In a power system, one fault may cause a subsequent chain of faults to occur. Some form of guidance such as proposed emergency operations to prevent overload of normally functioning apparatus should be a part of such an expert system for fault diagnosis.

To this end, the user–interface often incorporates network diagrams that are displayed on graphics displays in addition to standard text output so that operators can easily recognize the fault location, area in outage and other states of the network [4], [8]–[10], [33], [34].

Figure 8 shows examples of fault diagnosis flowcharts that are displayed by the expert system for a substation [9], [33]. In this example, a diagram of the substation where the fault occurred and the corresponding information tables were displayed at the request of the operators. Following this display, the diagnosis results are displayed on the operator's console which include the fault type, the fault location, the area in outage and additional messages. The important point here is that the expert system should not be a *black box* to the operator. The expert system should display to the operators the information it used in making the diagnosis, as well as the condition of the network in the vicinity of faults. The diagram in Fig. 8 shows the network configuration, the interrelationship of protective relays detecting the faults, and the circuit breakers that are tripped to isolate the fault from the rest of the network.

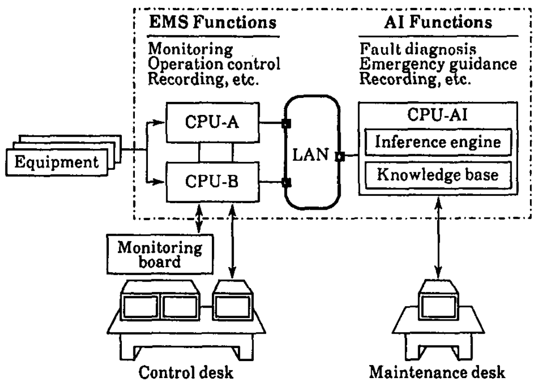

Fig. 7. Configuration of a loosely-coupled system for fault diagnosis.

C. Expert System Shell

In the past, expert systems were built using artificial intelligence languages such as LISP or PROLOG. Almost all expert systems are currently built using expert system shells that provide an inference engine and knowledge base management system. These tools normally use production rules and frames as the knowledge representation. They also provide a linkage mechanism for interacting with traditional programming languages, such as FORTRAN and C.

Recently, some research into special expert systems that feature inference mechanisms and knowledge representations tailored for power system applications has been presented [16].

For a practical expert system, particularly one for real-time use such as in fault diagnosis, inference performance and communication overhead involved in communicating with other processors are important. Moreover, such an expert system should be able to handle a large number of frames since the EMS that such systems are integrated with supervise a wide-ranging network that comprises a large amount of apparatus to be represented as frames. Several such special expert system shells for process computers that satisfy the above requirements have been developed and implemented in EMS systems [9], [4].

VI. Field Experience

A fault handling support system installed at the Fukuoka Control Center of Kyushu Electric Power Company and an operation supporting system for Shin-Ikoma Substation of Kansai Electric Power Company will be used as examples to discuss field experience with fault diagnosis systems.

The field verification phase of the fault handling support system at Fukuoka Control Center was completed in February 1990 and actual operation began in March 1990. The system makes extensive use of artificial intelligence in implementing such functions as fault diagnosis, fault restoration guidance, reliability monitoring and operation scheduling support. The power system fault diagnosis function is capable of identifying the fault location, nature of the fault and unwanted operation of protective devices from

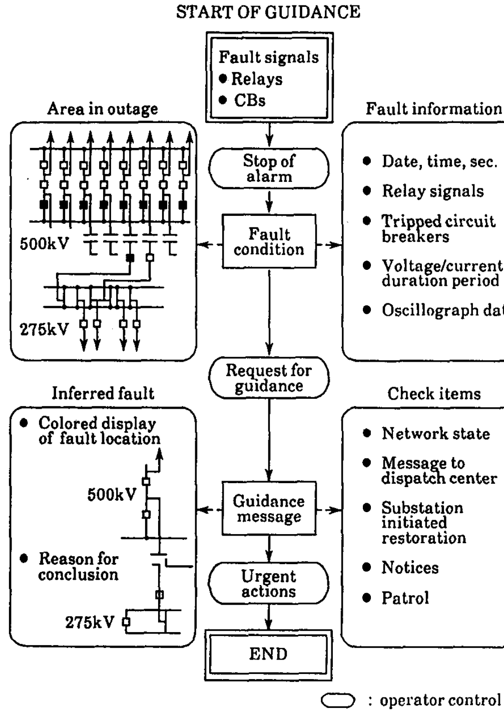

Fig. 8. Flow of expert system guidance.

on-line information such as operating relays and circuit breakers that trip.

Some testing results of this fault handling support system are given in Table 4. Field testing using 50 cases that exercise all the system's knowledge resulted in correct diagnosis of every single case–not one error was encountered. All diagnoses were performed in between 20–30 s well within the maximum 30 s that an operator is used to waiting. Since the start of actual operation, only one fault of the system facilities (transducer for power transmission) has been encountered. In this case as well, the system made the correct diagnosis. In the course of field testing and actual operation thus far no serious problems with the system have been encountered.

The operation support system for Shin-Ikoma Substation comprises knowledge-based functions such as fault diagnosis, restorative operation guide and maintenance patrol guide functions. The system was installed and started operation in 1987 [8], [9]. In January 1991, the system was evaluated based on a survey of 23 managers and supervisors of operation and maintenance. Respondents were asked to rate their degree of expectation as strong (3 points), medium (1 point), or none (0 points). Concerning the fault diagnosis function, information on fault conditions was given 69 points and fault location was given 67 points, nearly equal to total satisfaction [35].

Several fault diagnosis systems have been undergone field verification or actual operation and some points for improvement have been identified. The first point is di-

Table 4 Field Testing Results of Fault Diagnosis Function

Type of fault	Diagnosis accuracy		Inference time
	Correct	Incorrect	
Single fault	30 cases	0 cases	20–30 s
Multiple fault	20 cases	0 cases	20–30 s
Total	50 cases	0 cases	–

agnosis accuracy. To the present there have not been any incorrect diagnoses, but the diagnosis accuracy can be improved. The second point is improvement of the verification method. In order to test a greater number of cases, the expert system could be connected to a training simulator or other such systems. The third is evaluation criteria of the fault diagnosis system. At present, such evaluation is largely dependent on qualitative evaluation of the operators, making objective judgment difficult. If an objective method of evaluation can be established it will aid the dissemination fault diagnosis systems.

VII. Associated Functions

Up to this point the discussion has centered on transmission network fault diagnosis systems which form the bulk of fault diagnosis systems for power systems. In this section, some expert systems that provide other associated functions are presented.

A. Expert Systems for Protective Device Coordination

In order to perform fault diagnosis of power systems with high accuracy, it is a prerequisite that protective relay parameters are correctly set. Relay setting parameters are dependent on the power system configuration and must be changed when the network operating configuration is changed. This work requires the knowledge of a protective relay engineer and is time-consuming. This work is, in fact, becoming more difficult as power system configurations continue to grow in complexity.

In order to provide computer support for such work it is necessary to incorporate the expertise of a protective relay engineer. An expert system has been proposed for such a purpose [36]–[42]. In [36], an expert system for setting protective relays in a high-voltage transmission system is described. In [37] and [38], a protective device coordination system for relays, fuses, reclosers, and interrupters in a distribution system is discussed. In both cases, prototype systems have been developed. The current implementations incorporate all the general device types. All that remains to configure a practical system is to implement the remaining specific device variations. Their usefulness has already been demonstrated.

B. Expert Systems for Fault Diagnosis of Distribution Systems

Fault diagnosis is just as important for distribution systems as it is for transmission networks. In [24], [43], and [44] expert systems that locate faults in distribution systems are presented. The same basic method is used to locate faults in distribution networks as in transmission systems. However, in a distribution network a large amount of apparatus is distributed over a large geographical area, and only a very small amount of on-line information concerning operation of circuit breakers and other devices is transmitted to control centers and customer service centers, or is not transmitted at all. As a result, limited input information such as gleaned from trouble calls from consumers must be used with heuristic knowledge in order to infer the location of the fault. Such heuristic knowledge includes the following:

1) terrain conditions and their possible influence on location of the fault;
2) weather conditions (e.g., the probability of faults along overhead transmission line sections in forests is higher than in fields when the wind is strong);
3) often overloaded distribution facilities;
4) branching points that are vulnerable to outages induced by rats.

C. Expert Systems for Fault Diagnosis of Power Systems with Automatic Switching Devices

Power systems that incorporate auto-reclosing devices that reclose circuit breakers after the offending fault has been relieved, or automatic sectionalizing switches that minimize the area in outage due to the fault are not uncommon. It is also not uncommon for such circuit breaker status information not to be inputted to the corresponding control center. In order to realize a practical expert system such problems must be dealt with. This problem is discussed in [45] and [46]. Rules that can locate the faulted section based on telemetered data and the intended functions and settings of automatic switches and circuit breakers are registered in the knowledge base. In addition, the status of unsupervised switches is inferred from a log of all circuit breaker operations on the faulted line and knowledge pertaining to automatic switching principles.

VIII. Conclusions

Knowledge-based systems for fault diagnosis of power systems are being put into practical operation. They are proving extremely effective for fault diagnosis support of complex faults and unwanted operation of protective devices.

However, it is desirable to further increase the accuracy of fault diagnosis. This can be achieved by

1) detailed relay and circuit breaker operation information, and sensor (installed when required) information that reveals the status of the network;
2) higher-level inference that allows more detailed identification of fault locations and causes (e.g., case-based inference and model-based inference);
3) addition of auto-learning function;
4) higher-speed inference;

5) enhancement of special expert systems for simple and reliable extraction and maintenance of knowledge;
6) a user interface that allows the diagnosis results to be visually displayed to the operator.

It is likely that knowledge-based systems for fault diagnosis support of power systems will come into general use as they are integrated into EMS and SCADA systems.

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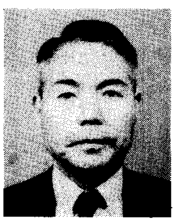

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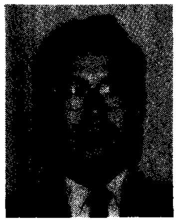

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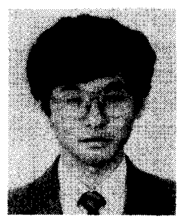

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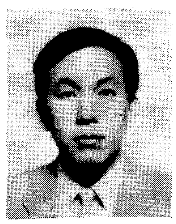

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