FAULT ANALYSIS USING INTELLIGENT SYSTEMS

Panel Session

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Abstract: Automating the fault analysis procedure has been a goal of many recent utility industry projects. The use of intelligent techniques in implementing desirable solutions is emerging as a quite promising approach. The IEEE Power Engineering Society (PES) presently has four committees that have formed either a subcommittee or a working group to look explicitly into the utility applications of intelligent techniques such as expert systems, neural nets, fuzzy logic, genetic algorithms, etc. The four committees have decided that the application of intelligent techniques in performing an automated fault analysis is a topic of joint interest.

As a result, a panel session sponsored jointly by the four committees has been organized and the contributions of the panelists have been summarized in this paper.

Keywords: Fault Analysis, Expert Systems, Neural Nets, Fuzzy Logic

INTRODUCTION

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Fault analysis is a widely used term that may have different meanings depending on the application of interest. The most common applications covered by the mentioned term are:

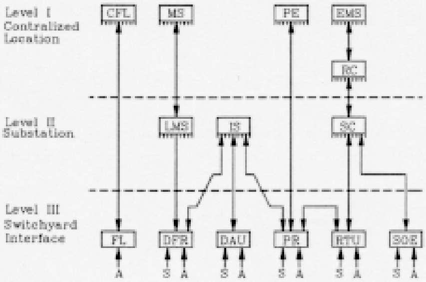
- interpretation of the alarms associated with faults
- analysis of the operation of protective relays and associated switching equipment
- identification of the faulted section
- location of the faults
- determination of the power system switching state after the protective relay operation

The ultimate interpretation of the term and associated applications comes from the personnel responsible for designing or using the equipment aimed at dealing with the power system fault. The most common utility groups that may deal with the fault events and their consequences are:

- protection engineers
- dispatchers
- maintenance crews
- engineering design staff

In order to further clarify the fault analysis term and related applications, it is very important to understand sources of the field data acquired to carry out the tasks associated with a power system fault.

The field data may be acquired in the power system substations and generating stations using a variety of different equipment. An example of the typical equipment that may be used in a substation is given in Fig. 1.



CFL	–	Centralized Fault Location
MS	–	DFR Master Station
PE	–	Protection Engineer's Console
EMS	–	Energy Management System
RC	–	Regional Control Center
SC	–	Substation Computer
IS	–	Integrated Substation System
LMS	–	Local DFR Master Station
FL	–	Fault Locator
DFR	–	Digital Fault Recorder
DAU	–	Data Acquisition Unit
PR	–	Protective Relays
RTU	–	Remote Terminal Unit
SOE	–	Sequence of Events Recorder

Fig. 1. Typical Substation Data Acquisition Equipment

It is important to note that the equipment indicated in Fig. 1 has different properties regarding its data acquisition and processing tasks. The main differences are in the following equipment features:

- data sampling rate

- synchronization of the sampling
- type of input channels
- number of digital and/or analog channels
- type of transducers
- data storage capacity
- data processing and communication capability
- user interfacing features

As a result of different equipment characteristics, it becomes obvious that the fault analysis goals, objectives and final outcomes may be heavily dependent on the data acquisition equipment used.

The use of intelligent systems relates to the fault analysis automation using advanced techniques such as:

- expert system
- neural nets
- fuzzy logic
- genetic algorithms

This Panel Session deals with various aspects of the specification, design, development and application of different solutions for the automated fault analysis using advanced intelligent system techniques and tools. In order to provide an overview of the variety of issues associated with the fault analysis automation, the Panel consists of experts from the utilities, vendors and academia. The utility representatives (REN–Portugal, HL&P–U.S.A., EdF–France) will present requirements and application experiences for the transmission, distribution and power plant applications. The vendor representatives (Siemens–U.S.A., Mitsubishi–Japan) will offer their view on the advanced concepts for the solutions and related products. A representative of the academia (University of Washington–U.S.A.) will give a prospective of some future trends in this field.

REN APPLICATIONS FOR INCIDENT ANALYSIS AND MAINTENANCE MANAGEMENT

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Main Incentives for the Applications

Rede Eléctrica Nacional (REN) is the enterprise responsible for dispatching and electricity transmission in Portugal and belongs to EDP Holding.

At present, REN's transmission grid has 150, 220 and 400 kV lines, with a total length of about 6000 km and is strongly interconnected with the European grid. It includes 43 substations with 14,000 MVA of transforming capacity.

To monitor and control the transmission gird, REN has in service, since 1987, a SCADA/EMS system for the National Dispatch and the two Regional Control Centers. Also, since 1982, REN followed a strategy to withdraw human operators from substation control rooms. This implied to follow a coordinated action to progressively install, in every substation, sequence of events recorders, remote terminal units and powerful programmable logic controller based automation equipment. The automation equipment exists in about 75% of REN's substations and namely performs undervoltage load shedding, restores service after the load shedding operation and executes delayed automatic reclosing after line tripping [1].

In terms of substation maintenance, there is a restricted number of maintenance teams, each of them located near a main substation and having to assist, beyond this one, several other "satellite substations." It is, therefore, quite important for the maintenance team to be able to access "useful" information about the faulty elements and the type of fault before starting an intervention.

REN's control center operators are "submerged" in information whenever an incident occurs in the network, involving several substations. The interpretation of the incident is not trivial because alarm data is limited (7 alarms per feeder) and service restoration must take into account the automation equipment actions.

Those were the main incentives for REN to start, in 1988, a project to help control center operators in incident analysis and service restoration, providing to them, in real time, the results of an intelligent treatment performed on the sequence of event recorder data (and also over functionally integrated control systems' event data). The project is also aimed at maintenance optimization by providing to the maintenance teams relevant data about incidents and faulty elements concerning substations under their responsibility and alerting them to possible future faults.

This project has been developed by a commercial vendor in close cooperation with REN, that has been involved in the specification, expert knowledge contribution and development of some related software applications.

Implementation Issues

The new equipment consists of one industrial AT–compatible PC installed in each REN substation serially connected to the sequence of events recorder or to the integrated control system, and also PCs located in the control centers, in the maintenance and protection engineering centers, etc. The communication between the PCs is established via REN's switched telephone network (mostly supported on radio links).

The application software, developed in C and C++, runs in a multitasking environment. The man–machine interface is menu driven and complies to an international standard.

To achieve a single development system, the software includes several interfaces for dialog with different acquisition systems to retrieve from them selected event data. Also, to achieve a consistent global information system, to enable a less complex intelligent treatment and to minimize the diversification of software interfaces, each acquisition system's data base was revised and standardized in terms of the feeder type data, system data, control equipment data, etc.

Other important issues to ensure the correctness of the intelligent treatment were data accuracy (10 ms events resolution) and data synchronization – every substation has an external radio clock receiver which namely synchronizes data acquisition.

Intelligent incident analysis filters non relevant data, reasons about the incident and generates concise conclusion messages describing the incident and providing to the operator some restoration hints. It must, therefore, perform a diagnosis in a time compatible with real time operation, which is not available by conventional alarm sorting methods. The implementation choice was, then, to adopt a knowledge based approach and to incorporate the decision logic. This issue has a drawback caused by the need to recompile the software, namely each time a new set of rules is added. Nevertheless, the alternative to develop (or select on the market) a special expert system to run this function and interface with the existing network monitoring and control software, seemed at the beginning to be less cost effective, more demanding in terms of required development time and with more potential integration problems.

Since 1992, when this intelligent treatment began to be used, the knowledge base has suffered modifications as a result of the introduction of improved rules. This has not been a major problem, since the software includes the facility to have itself and its dependent files remotely updated from a maintenance center.

The performed intelligent treatment [2] is based on the same data contained in the event messages already classified by the "family codes" according to its type and intended treatment. The family code describes the source of the event, for instance, a line feeder circuit breaker change or the alarm trip generated by a protection. Regarding the sequence of all the events that belong to the same feeder and occur within a certain period of time, it guides to the final conclusion. Intelligent analysis also takes into consideration a second level of interpretation – concerning incidents that involve HV lines (and thus involving more than one substation) – which is performed by the maintenance teams and the main PC located at the Regional Control Center.

Once an incident is detected locally, the relevant data is evaluated and the conclusions of the reasoning about the incident are automatically transmitted to the related maintenance team and from there to the main PC at the Control Center (taking a few seconds, one minute at most). The maintenance personnel (or Control Center operators) may also, at any time, access remotely (on demand) the involved PC to obtain discriminated information.

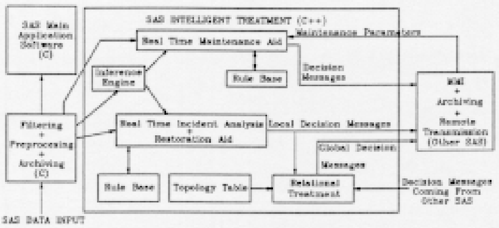

Fig. 1. The Software Architecture

An example of the decision messages received at the Control Center after an incident (involving a line **LAI/LBI** connecting substations **A** and **B**, where B is a maintenance team substation) is as follows:

StB 12/12/95 15:17:27:41 LAI Three phase trip
12/12/95 15:17:27:71 LBI/LAI tripped and
reclosed at StA end
StB LAI–OPA will restore service after 1 minute

In terms of maintenance management, a statistics module has been developed to perform calculations, basically on a monthly basis, using each substation data, e.g., to determine out of service time per line feeder; counting the number of normal switching operations per breaker since its last servicing and doing the same for breaker trippings, etc.

Demonstrated Benefits and Future Trends

The project includes features that meet the demands for a better operation of the Portuguese transmission grid and follows maintenance management requirements.

The new equipment is now spread over 83% of REN's substations and is in practical use by the Control Center operators and maintenance personnel. In practice, the devices are consulted when incidents occur as well as in normal daily supervision and also to perform maintenance actions, thus contributing to a more efficient intervention in unmanned substations.

An important feature of the project is its ability to be used at any level of transmission substation supervision, whether locally or remotely – from main substations, from control centers, from maintenance and protection engineering centers, etc. The intelligent treatment is performed in a decentralized way, so that information is only treated and related at the level of concern: locally, or at the Control Center levels. The results of this intelligent treatment are quite accurate as they are performed over synchronized, chronological and selected events.

The knowledge based approach used for incident analysis and to calculate some data for maintenance management purposes is still under evaluation. Software modifications are being made to move knowledge rules outside the program code, and thus to convert the knowledge based sections of the software into a real expert system.

As REN is undergoing a major project to upgrade its existing SCADA/EMS, it will profit to vertically integrate the relevant information concerning intelligent incident analysis.

This information from the new equipment will be presented at the Control Center as a part of the SCADA graphical user interface, and namely at the substation one line diagrams, at a specific view port next to each feeder. This view port will contain symbols corresponding to three different groups of decision messages (the diagnosis of the incident, the hints for restoration actions and the messages generated after service restoration). The communications support will be more reliable then, as this data will flow over the same communication network which will be the back bone of the upgraded system.

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HOUSTON LIGHTING & POWER COMPANY APPLICATIONS: 345 KV SUBSTATION AND POWER PLANT GENERATOR

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345 KV Substation Application

A common practice in Houston Lighting and Power (HL&P) Company is to collect transmission system disturbance and fault data by digital fault recorders (DFRs). This data is used for post mortem analysis. Important goals of the analysis are either to identify misoperation or to confirm correct operation of relays and breakers during faults. For this purpose, substations are equipped with a total of 23 DFRs which can communicate to a computer located in the protection engineers' offices.

One of the main problems encountered in trying to utilize DFR data is the large number of disturbances and fault records captured. Manual search to identify fault records of interest is time consuming. In particular, it is time consuming to distinguish between fault transients and other transient events that may trigger the recorder, but do not actually represent a fault event.

Therefore, the main problem to be resolved is to automate both event classification and analysis of fault events. As a result, an expert system was specified as a possible solution to this problem [1,2]. The following two steps were identified as the main focus of the expert system design:

- Fault Detection
- Fault Diagnosis

The knowledge necessary for disturbance analysis was acquired by interviewing experts (protection relay engineers) and by using an empirical approach based on the Electromagnet Transient Program (EMTP) simulation studies. The reasoning process includes the following steps: fault detection fault classification; event analysis; protection–system and circuit–breaker operation analysis; fault location calculation.

The reasoning required to perform classification and analysis of the event is implemented by using a set of rules. The reasoning process is separated into two stages. In the first stage, the system reasons on the basis of the analog–signal parameters, and in the second step, it reasons by using the protection–system parameters. Analog–signal and protection–system parameters are obtained by post processing the DFR recorded samples and extracting the relevant features of the signals recorded on the line that had experienced the largest disturbance. The system set–up is shown in Fig. 1.

The analysis starts once the event is transferred from the DFR to the Expert System computer. The expert system then converts only part of the event file (two cycles prefault and a minimum of 15 cycles of fault data) from DFR binary format to a MATLAB [3] binary format in order to speed analysis. After conversion is completed, signal processing is started. Current and voltage amplitudes for the line with the most significant amplitude change are determined for the prefault, fault and post fault intervals. Protection system operation parameters are extracted and passed to the "artificial intelligence" diagnosis module for processing in the form of "if–then" rules.

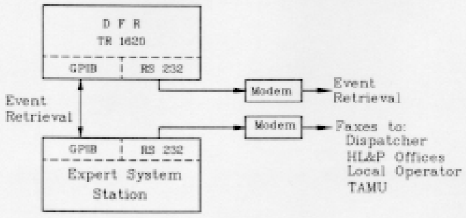
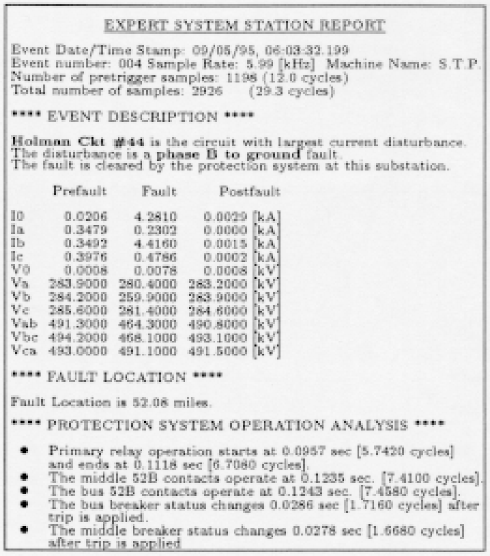


Fig. 1. Expert System Set–Up



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                    EXPERT SYSTEM STATION REPORT

Event Date/Time Stamp: 09/05/95, 06:03:32.199
Event number: 004 Sample Rate: 5.99 [kHz]  Machine Name: S.T.P.
Number of pretrigger samples: 1198 (12.0 cycles)
Total number of samples: 2926     (29.3 cycles)

**** EVENT DESCRIPTION ****

Holman Ckt #44 is the circuit with largest current disturbance.
The disturbance is a phase B to ground fault.
The fault is cleared by the protection system at this substation.

      Prefault     Fault    Postfault

I0     0.0206     4.2810     0.0029 [kA]
Ia     0.3479     0.2302     0.0000 [kA]
Ib     0.3492     4.4160     0.0015 [kA]
Ic     0.3976     0.4786     0.0002 [kA]
V0     0.0008     0.0078     0.0008 [kV]
Va   283.9000   280.4000   283.2000 [kV]
Vb   284.2000   259.9000   283.9000 [kV]
Vc   285.6000   281.4000   284.6000 [kV]
Vab  491.3000   464.3000   490.8000 [kV]
Vbc  494.2000   468.1000   493.1000 [kV]
Vca  493.0000   491.1000   491.5000 [kV]

**** FAULT LOCATION ****

Fault Location is 52.08 miles.

**** PROTECTION SYSTEM OPERATION ANALYSIS ****

  •  Primary relay operation starts at 0.0957 sec [5.7420 cycles]
     and ends at 0.1118 sec [6.7080 cycles].
  •  The middle 52B contacts operate at 0.1235 sec. [7.4100 cycles].
  •  The bus 52B contacts operate at 0.1243 sec. [7.4580 cycles].
  •  The bus breaker status changes 0.0286 sec [1.7160 cycles] after
     trip is applied.
  •  The middle breaker status changes 0.0278 sec [1.6680 cycles]
     after trip is applied
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Fig. 2. Expert System Fault Report

The conclusion part of the rules is written in the form of short descriptive English phrases. Several phrases are combined to make a single statement appearing in the final analysis report with is faxed to appropriate operations and engineering personnel. An example of a typical fault analysis report is given in Fig. 2.

Ninety–four events were analyzed in the period from June 1994 to August 1995. It takes approximately 3.5 minutes from the time of event recording by the DFR until the event analysis report is faxed to the first site. The expert system software has always picked the right transmission line for a true fault event and the calculated fault location has compared favorably with short circuit study data for faults on transmission lines directly connected to this substation.

Power Plant Generator Application

It has not been common practice in Houston Lighting & Power Company to collect power plant generator disturbance and fault data by digital fault recorders. Based on the favorable experiences obtained from the transmission DFR's and expert system a power plant generator application utilizing a new DFR and real time expert system is being pursued. The following design criteria were established in order to cover a wide range of generating stations:

- provide continuous sampling and monitoring of input data
- provide synchronized data sampling that automatically align all monitored electrical quantities in time
- provide redundant checks and indication to determine if sensor readings are erroneous
- provide historical data and trends for most important electrical quantities
- check that all readings are within expected limits
- check trends to determine if continuation of the present mode of operation will take the generator unit outside the allowable range for the electrical quantities
- provide alarm limits that can be variable, i.e.,
- recalculated for each specific operating level
- provide "early warning" of operating problems
- provide concise and condensed measurement and event information to aid the operators in making decisions
- provide digital synchroscope and monitoring of the synchronizing procedure to help operator synchronize the generator with the system
- provide storage of historical data and recovery capability using data compression techniques
- provide modular design allowing easy adaptability and expandable for future use on other generator units

The system set-up is shown in Fig. 3.

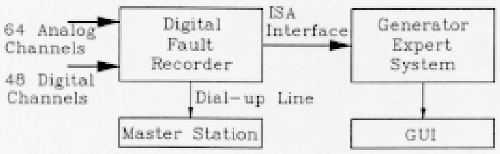

Fig. 3. Generator Monitoring Expert System Block Diagram

A Digital Fault Recorder (DFR) serves as a data acquisition front-end, providing continuous data flow toward the expert system PC. At the same time, the DFR maintains its basic function of recording the events according to the internal triggers and storing those events on the local hard drive inside the recorder. These stored events are available remotely per request over a dial-up line, using master station software provided by the DFR manufacturer.

The initial set of expert system application functions which will be implemented are [4]:

- voltage unbalances
- current unbalances
- excessive V/Hz detection
- negative sequence current detection
- loss of field detection
- 100% stator ground fault detection
- generator trip analysis
- generator speed
- rotor subsynchronous resonance
- capability curve limits and operating point
- synchronizing generator to the system
- performance analysis of the synchronizing procedure

All of the above functions are integrated using an "upper level intelligence" module. Algorithms are used in the signal processing part of the expert system for calculation of necessary parameters. Settings and thresholds for every application are stored in the database. Alarms and system messages are displayed on a screen in real–time for use by the operators. Also, the displayed messages are logged together with data in a time stamped report.

The system is anticipated to begin on–line operation in early 1996.

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EDF APPLICATIONS AT POWER PLANTS, SUBSTATIONS AND DMS

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Work in artificial intelligence began at Electricite de France (EDF) about ten years ago. Many projects were launched, but few remain, most in the diagnosis and fault analysis field. The main applications will shortly be presented, beginning with power plant applications, applications at the substation level, and ending with the (distribution) dispatching level.

Nuclear Power Plants Maintenance

In order to make the right decision about components of a power plant, monitoring aims at providing maintenance operators with convenient information. To improve the usefulness of provided information two directions are followed:

- to improve monitoring systems so that they receive, analyze, process, store and display the most relevant information,
- to complement monitoring capabilities with diagnostic systems that will provide an interpretation of an observed behavior in terms of component malfunction.

The first direction has been the guideline for the definition of a new integrated monitoring architecture for EDF nuclear power plants. The system has a flexible architecture which allows the connection of different monitoring systems for various components of the plant (turbine–generators main coolant pump, internal surveillance, loose–part detection, inlet valves...). Data is collected in a database. Different data processing functions can then access this data to provide users with elaborate computations, visual presentation of significant evens, etc. The system can be used locally in a plant and can also be accessed by central experts through a national network. The first system was installed in a French nuclear power plant in 1995.

The second direction leads to the definition of diagnostic systems which propose an interpretation of observations. Within the new system framework, three subsystems are under development: one which deals with turbine–generator diagnosis, one for reactor coolant pump diagnosis and one for assisting in the **loose–part diagnosis** (which is in an earlier development state than the other two).

Intended users for these systems are power plant maintenance specialists and central experts (who have to deal with knowledge base maintenance). The basic requirement is to provide a "convincing" diagnosis for the component under study. Both of the latest developments use a knowledge based system approach.

The first subsystem relies on a heuristic classification process, trying to match the current case with predefined characteristic situations. It can identify about thirty generic faults in steady speed, start–up and slow–down conditions. Some 90 typical situations are handled by the subsystem. The turbine–generator diagnosis subsystem is the result of a cooperation between EDF and a vendor. The first installation in a power plant of the industrial product took place in December 1995.

Besides using heuristic classification among situations, the subsystem for coolant pump diagnosis uses "deeper" knowledge such as cause–to–effect propagation of faults and events or structural description of the pump. The cooperation between these different types of knowledge is done through a blackboard architecture. The subsystem can identify about ninety fault scenarios, each of them providing explanations of the abnormal observations and predictions of the forthcoming events implied by the current state of the pump. The prototyping, which ended in the first half of 1995, is the result of a cooperation between EDF and a vendor. After an evaluation of the prototype, the decision to turn it into an industrial product was taken in June 1995.

The main lessons learned from these developments are that:

- A lot relies on the quality of the cooperation between the different parties involved (experts, knowledge engineers, software developers, future users...). In these projects, the high level of motivation of every party was a key element of the success of the developments.
- A high quantity of work is necessary for knowledge acquisition and validation.
- Knowledge modeling and structuring play a key role as they provide both a framework for efficient knowledge acquisition, and the basic structure for software development and maintenance.

Applications Dealing With Maintenance at Substation Level

Two systems allowing analysis of data recorded in substations during incidents mainly for maintenance purposes have been developed. The end–users are engineers or technicians in charge, either of the transmission network protection equipment (in one case), or of the distribution network quality (in the other). In both cases, the processing is "centralized", based on the analysis of the recording files automatically fetched from the substations through the switched telephone network.

The system that aims at the transmission network was designed to analyze the protection system operation. Indeed, early detection of malfunctioning relays or breakers, incorrect settings or ratings depends almost entirely on a careful scrutiny of the protection system operation after faults occurring on the network.

The heart of the system is based on expert systems methodology. The schema of the reasoning may be presented as successive steps: extracting the information that seems relevant to an incident, analyzing the correct or incorrect behavior of the various relays and breakers involved, "voting" to define the location of the fault, re-analyzing the operation of the various pieces of equipment considering this location.

The system was in experimental use in two regions during a few years and the approach was proved fully effective, but deployment was not pursued for organizational and technical reasons. The first drawback was the need for very accurate data on relays, breakers, actual ratings. At the present time, this information is not in databases or not fully reliable. This situation may change as a new system for network monitoring will be deployed in the near future; the lesson is perhaps "ne mettez pas le charrue avant les boeufs" (**don't put the cart before the horse**). A second drawback, not yet fully solved, is the need to update and adapt the expert system rules, depending on peculiarities of the equipment of substations. This is a really difficult problem for that type of system: do we need a "knowledge engineer" each time the system is to be used for a different substation, or are we able to define rules editing devices enabling end–user to tailor each application?

The case of the system aimed at the distribution network quality is better.

What is the motivation behind the distribution system application? EDF has developed a method, named "auscultation" which consists in analyzing all the electrical incidents affecting a distribution feeder and identifying the sources of transient faults. Feeder "auscultation" used two types of equipment: a fault recorder, installed at the HV/MV substations recording voltages, currents and logical information form the protection system; fault detectors installed along the feeders and noting faults (time-stamped) on the downstream portion of the network.

The system is, in fact, an aid to fetch first, then analyze the wealth of collected information. It allows for qualitative and statistical analysis of the faults, localization of the faults based on impedance computation of the fault loops. It allows for a succinct monitoring of the protective system (more succinct than for the transmission network application) and also for an object-based expert system based identification of the type of fault.

As a matter of fact, the system is spreading and a few EDF distribution centers are using it, but probably its most appreciated features are not connected to artificial intelligence technology: automating the gathering of data, editing of short incident reports, localizing faults and outputting files for statistical use with EXCEL or LOTUS! We may say, that in that case, that the horse was put before the cart. An now, it begins to be possible to change the horse into a tractor, if we want to.

Incident Analysis and Restoration at Distribution Dispatching Level

This is a new application still under development. A part of this new development is devoted to restorative control after incident; to do that incident analysis is more or less mixed with remedial actions. Another part is a simple events synthesis in order to give the dispatcher a more synthetic view of what is going on. So the major technical incentive is quicker restoration after incident. (Another incentive was more "political".)

Of course, an underlying hypothesis is the quality and accuracy of the data needed and stored, or acquired, in the databases of SCADA and DMS system.

As for the development of the new system, the technology used is "object oriented", with a high-level programming language. Task modeling techniques are used for the restorative control part. The connection with the SCADA will be made through cleat Application Programming interfaces. A side effect of the definition with the vendor of these interfaces, was a better understanding of the system.

The system should be put into use at Lyon and Versailles in 1997, and at Nimes (also in 1997), connected to a system under development at EDF. We hope, in fact, that the connection through application programming interfaces will allow for easy connection with different SCADA systems. Afterwards, new functions, such as model-based events synthesis, should be developed and put progressively into this new system.

One of the lessons learned is that the real-time connection to a SCADA is not an easy job and requires at least as specialized skills as artificial intelligence. Another lesson is that the choices made for development, high-level language and incremental cycle of development, are really necessary for that type of application.

KNOWLEDGE BASED LOCATION OF TRANSMISSION SYSTEM FAULTS: DESIGN AND IMPLEMENTATION

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Following the occurrence of a fault in a power system, the system operator must determine the extent and location of the fault and then proceed to restore service to the affected area. The accurate determination of the fault location and the various pieces of equipment involved in the disturbance can be a complex process depending on the extent of the failure (i.e., the presence of multiple faults) or the misoperation of protecting equipment such relays and circuit breakers. Under such conditions, the number of candidate locations for the fault increases dramatically making the diagnosis process very complex and risky. Moreover, the dispatcher is expected to diagnose the fault and the existence of misoperations of equipment within a reasonable amount of time, making this problem one of the most challenging and stressful that system dispatchers have to face on a daily basis.

From an operator's point of view, a fault manifests itself by a set of alarm messages signaling the opening of breakers and the operation of relays. Based on these symptoms, the operator must determine where the fault is located and what equipment can be put back in service. For simple cases which involve only a single fault and for which the protection system worked properly, this requires only fairly simple and straightforward reasoning. If two or more faults take place at approximately the same time, it may be harder to separate the symptoms or even to recognize the existence of distinct problems. If some protection devices fail to operate, the number of possible locations for the fault increases dramatically and the operator must select the most likely location among the plausible hypotheses.

Rule-based expert systems have the capability to accomplish this complex type of diagnosis fast and reliably. Various proposals to use expert systems for system fault diagnosis have appeared in the literature. One of the earliest approaches is the one of DyLiacco and Kraynak [1]. More recent work includes the work of Talukdar, et. al. [2], Fukui and Kawakama [3], and Kezunović [4].

Design Overview – Structure of FDS

The Fault Diagnosis System (FDS) is activated whenever the SCADA system detects a relay operation in the network. Fig. 1 provides an overview of FDS. Since the consequence of a fault can crate some activity spread over a period of time, FDS waits for a few seconds to make sure that the situation has stabilized before it starts a diagnosis. Inputs to the diagnosis activity are obtained from the SCADA data and include breaker statuses and real-time relay information. In addition, FDS accesses the network database to gather any network data (relay protection information, zone coverages, etc.) needed for the diagnosis.

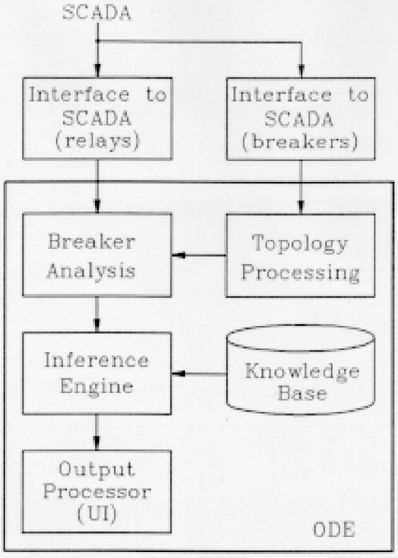

Fig. 1. FDS Overview

The diagnosis is based on the use of "generate and test" paradigm and proceeds as follows:

All the possible locations for the fault, such as a line, a busbar, a transformer, etc., must first be determined. Contributions to this list of hypotheses originate from two sources:

- A topological algorithm that uses the breaker status information to determine the de-energized network(s). Any piece of equipment included in this network is a possible candidate. If two or more separate de-energized networks are detected, a multiple fault is postulated and the hypotheses list is built accordingly.
- This list is augmented by all the equipment located in the zones covered by the primary and secondary relays activated by the fault.

The hypothesis list is then filtered to remove from consideration hypotheses which can be ruled out for obvious reasons, such as a facility being out of service for maintenance. Default certainty factors (CF) (that is, a priori reasons for believing in the particular hypotheses) are then assigned to the hypotheses on the list.

Each of the remaining hypotheses is then tested using the fault diagnosis rule-base and the available relay signals. Whenever a hypothesis satisfies the conditions specified by a rule its certainty factor is adjusted to reflect its increased likelihood. Some postulated fault locations imply the misoperation of one or more devices. The certainty factor of these hypotheses must be decreased to reflect the unlikelihood of such events. The CFs are fuzzy membership levels of the hypothesis and are manipulated using fuzzy logic [5].

Finally, the list of hypotheses is sorted in decreasing order of plausibility and presented to the operator. Each hypothesis is described by its type, the fault location(s), the implied equipment malfunction(s), and its likelihood or membership (given by the CF). The list of hypotheses is presented to the operator as one or more User Interface displays. More than one diagnosis case may be accessed and viewed through the use of this standard user interface.

Necessary Data

Diagnosing systems faults requires data about the network, the protection system, as well as the real-time status of breakers and relays.

Network elements are denoted by two classes: a class of *connections* including all the circuit breakers and a class of *segments* comprising every element which is not a circuit breaker. Segments include power equipment such as generators, transformers, transmission lines, and protection equipment such as relays. Most types of protective relays are supported including distance relays, differential relays, breaker failure relays, etc. Network elements are represented in the same format used by other EMS applications.

Since FDS is intended for unassisted, on-line use, all its real-time information must be provided by SCADA. When an unintended circuit breaker or relay operation takes place in the network, SCADA provides the name of all the breakers and relays which have operated. The distance relays are classified according to signal type as primary, high impedance and ground.

Modern relays generate many signals characterizing the faults. Due to the high cost of wiring these signals to the substations' computer and the limited capacity of the telecommunication links, only a limited subset of the signals is available for on-line analysis. The presence of additional signals, however, improves the potential ability of the FDS to discriminate between plausible fault locations. On the other hand, the design of the system must be such that the absence of a particular signal should not prevent the system from finding at least one reasonable hypothesis.

Types of Knowledge

The knowledge used in FDS is obtained from extensive discussion with utility system operation and system protection personnel. Two modes of rule generation are used:

- Rules obtained directly from the appropriate experts
- Rules obtained through case analysis

The second type of rules are obtained through extensive simulation and analysis of actual observed cases. Each case consists of a description of the type of observed fault, the list of disconnected equipment, the list of breakers involved in the disconnections, and a list of relay operations. In addition, design data on the protection system is also used to create the rules. These data include information associated with the various relay models used, the expected signals generated by the relays, and the zone coverages of each of the appropriate relays.

The study cases are executed using FDS to tune the final confidence factors and rules. The correct tuning of the confidence factors is based on the repeated simulation of the set of test cases. These test cases must be rich enough to permit the proper calibration of the CFs to achieve correct discrimination. It is possible, however, to converge to a set of satisfactory confidence factors after a few passes through this analysis.

Heuristic knowledge entered in FDS serves two purposes:

- Identification of device malfunctions and misoperations
- Adjustment of the membership values (certainty factors) associated with the hypotheses

Two types of devices can malfunction: relays and circuit breakers. Malfunctions and misoperations of these devices are detected using production rules.

Rules are used to adjust the certainty factors of the hypotheses. It is clear that the certainty factors of the rules must be tuned to ensure that the system consistently places the most likely hypothesis at the top of the list. Experience has shown that this tuning does not requires excessive time or expertise.

FDS has been designed so that it can be incrementally improved by the utility's engineers. As they enter more specific rules about their network, the discriminating ability of the system continues to improve.

Processing of Confidence Factors

FDS uses confidence factors (CFs) as the basis for the ranking of the fault hypotheses. A CF is a measure of the level of membership of a particular hypothesis in the set of faulted equipment. The membership level is a number in the range [0,1].

The *product–sum* membership combination algorithm is used to revise the levels of membership of the hypotheses. To compute the revised level of membership of hypotheses H, let CF_H be the prior membership of the hypothesis. Assume that new evidence E is obtained for the hypothesis H, denoted by CF_E. The new membership for H is given by:

$$\overline{CF_H} = \begin{cases} CF_H + CF_E - CF_H CF_E & \text{if } CF_H, CF_E > 0 \\ CF_H + CF_E + CF_H CF_E & \text{if } CF_H, CF_E < 0 \\ \dfrac{CF_H + CF_E}{1 - min\{CF_H, CF_E\}} & \text{otherwise} \end{cases}$$

If additional information corroborating or rejecting hypothesis H is received, the same formula may be used recursively.

Implementation

FDS has been implemented as an integral component of a suite of artificial intelligence applications. This suite is part of an environment for knowledge–based decision support in the EMS [6].

Whenever a relay operates, an alarm is sent and processed by the EMS Intelligent Alarm Processor. This processor, in turn, will signal FDS indicating the occurrence of a relay event. At this point, FDS will retrieve the alarm information and will pause for a number of seconds before starting the data collection necessary to proceed with the diagnosis. Because any relay action will be associated with a corresponding set of breaker actions, the Topology Processing function is used to determine the de–energized networks. From the SCADA database, FDS receives, in turn, all the relay points associated with the observed faults.

The Breaker Analysis component of Fig. 1, includes the following tasks:

1. Assembly of lists of equipment protected by the operated relay(s).
2. Identification of de–energized equipment based on the input received from the Model Update.
3. Determination of any blacked–out island(s) from the de–energized equipment. If more than one independent island is found, this will indicate the presence of a multiple fault.
4. Generation of lists of possible hypotheses for fault location(s), and associate breaker and relay operations with the components of the list.

Upon completion of Task 4, the inferencing process is applied to each of the hypotheses in the candidate list (Inference Engine block in Fig. 1). The results are then sent to an output processor for final display.

Conclusions and Comments

The problem of accurately determining the location of a fault in power systems after a disturbance is, clearly, a knowledge intensive activity requiring a great deal of operating expertise and knowledge about the various protection hardware and schemes used by utilities. FDS is a knowledge based system that can be used to help the operator determine the location of faults and possible equipment misoperation.

FDS has been used in the diagnosis of faults on complex large scale power systems. FDS does not produce a unique answer. Rather, depending of the circumstances, it considers many competing hypotheses, and by applying its knowledge to the available data, it produces a ranking according to the likelihood of occurrence for the various faults. The rankings produced by FDS are based on the use of fuzzy membership functions, and are revised by using the combination rules of fuzzy logic. These rankings show a relative classification of the possible outcomes for the location of the fault. The important aspect of these rankings is that they should, first, be accurate (that is, the actual location of the fault must be the hypothesis with the largest membership), and second, they must show sufficient separability between the actual location for the fault and any other competing hypotheses.

FDS does a good job with limited information and knowledge. If additional knowledge and SCADA data, such as relay zone information, is available to FDS, its discriminatory power is enhanced and flagging of spurious misoperations is avoided. The knowledge required may be obtained from the utility experts in system operations and system protection. The advantage of a knowledge based system such as FDS over more conventional software is its adaptability since more knowledge may be added in the form of rules without disturbing the basic structure of the program.

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FAULT DIAGNOSIS FOR POWER SYSTEM RESTORATION

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Major Incentives for New Applications

Fault diagnosis is indispensable for prompt and precise power system restoration. When a network fault has occurred, an operator in the control center has to judge and identify whether or not any power network components such as transmission lines, transformers and buses are subjected to the fault. After that, the components to be re–energized are determined. In this process of making a restoration plan, an operator's expertise can play an important part. The network fault diagnosis is expected to be one of the applications to support an operator's restorative operations during network disturbances.

Requirements for New Applications

In recent years, with an increase in the number of power networks under a control center, the behavior of faults has become complicated and the fault–affected area has broadened as a result. For these reasons, it is increasingly necessary that a control center operator, in the event of a network fault, quickly and accurately identifies the faulty section and determines the nature of the fault (based on information about the fault) and then issues restoration instructions. The new applications of diagnosing a network fault are mainly classified into three parts from a restoration point of view.

(1) Faulty Section Detection
In the process of power system restoration, the faulty sections that cannot be used for restoration due to their electrical damage have to be detected first of all. This judgment is performed using protective relay operations and their tripping circuit breaker information that are the only real time data transmitted to a control center during a network disturbance. Therefore, these detected sections include essentially ones that do (and do not) need the maintenance of the damaged network component for trial re–energizing. This faulty section detection has been performed by an operator. But for a human operator who has less experience regarding network faults, it is difficult to detect accurately faulty sections when multiple faults, or faults with complicated relay and circuit breaker operations have occurred.

(2) Fault Cause Estimation
Once the faulty section is determined, it is an urgent matter for an operator to decide whether or not the section can be re–energized. In most cases of transmission line faults by lightning strikes, the electrical fault could be eliminated by trial energizing. So, if the data concerning an estimated fault cause, such as lightning strike, bird/animal dashing, galloping and so on, is provided to an operator, it is very useful to judge the detected faulty section to be reusable for a restoration route with a trial energizing. To estimate a fault cause, in addition to real time data needed for faulty section detection, the information on time, season, weather, geography, and oscillography is also used. Except for the oscillograph data inputted by an operator, all required data can be received on line via an energy management system (EMS) and a weather information system.

(3) Faulty Section Isolation
The fault section isolation is very effective in the case that unrestored loads remain within an outage area having a faulty section. To isolate a faulty section, system operators are dividing the outage area into small sections and energizing each section. These trials are executed repeatedly. When a supply fault remains in a faulty section within an outage area after restoration, energizing search procedure is guided. Since subsequent operations are determined according to actual operation results, it is difficult to formulate energizing search procedure off–line in advance. For this reason, each time the system status is changed by the energizing search operation, the succeeding energizing search operations have to be automatically executed until the unrestored load is removed.

Implementation Strategies

Many knowledge based systems for fault detection have aimed at encoding the diagnostic knowledge of operators [1]. However, this approach to fault detection requires considerable time and effort to extract diagnostic knowledge, (described as symptom–fault associations) from operators prior to encoding. The problem with the approach is that it is difficult to extract all the knowledge for multiple faults because operators could not consider all possible situations at the same time.

Since the diagnostic task shell [2–4] has a built–in general diagnostic algorithm which is not limited to one application area, diagnostic systems can be constructed simply by adding an application model of a diagnosis target. The built–in algorithm performs a generate–and–test strategy.

The addition of a protective relay system model to the diagnostic task shell has made possible the faulty section detection.

Thus, facility maintenance or protective relay type change can be easily accommodated by adding or changing the relevant equipment or protective relay model. Moreover, when relay operation data at the time of a fault is summarized, the faulty sections can be diagnosed corresponding to the data level simply by changing the data summarization mode of the data transmission system.

Fig. 1 shows the general flow of the diagnostic algorithm and the models incorporated into the diagnostic task shell. The diagnostic algorithm first generates hypotheses of faulty sections from action data provided by the protective relay at the time of fault occurrence. Then, while simulating the protective relay and circuit breaker actions, it compares them to action data at the time of a fault. The hypothesis is judged as a faulty section whose simulation process corresponds to action data at the time of a fault. This simulation process is presented to an operator as reference data for determining which hypothesis is most likely to be correct.

The protective relay system model is comprised of power system components such as transmission lines and buses, protective relays, data transmission system, fault current circuits, and so on. The model contains various types of relays – not only fault–eliminating relays, but also transmission line reclosing equipment, trial cutting off relays, and substation protective relays to enhance diagnosis accuracy.

The determination of the cause of power network faults has also been done by an operator using information about the operating relay condition, weather, season, time, geography and other factors involved. This task often needs enough experience to narrow the possible causes down to a single one because all the necessary data cannot always be obtained and different types of fault rarely present characteristics unique to them. This is why a fault causes reasoning system has not be realized.

Through the implementation study, the possibility of using an artificial neural network (ANN) to help address the problem has been discussed. The ANN itself is apt to become a black box, making it difficult to provide an operator with grounds for reasoning results. To permit identifying the cause of a fault properly, a combination of an ANN and an expert system (ES) was adopted and this application has been incorporated into a practical EMS [5]. The system can also use the results of the oscillography data analysis to improve the accuracy of fault cause determination. The reasons for judgment made are given using the fault cause estimation rules applied by an ES. This information is helpful for an operator to see if the result of the estimation by an ANN is reasonable.

In estimating the cause of a fault, based on the past experience of operators, it is possible to eliminate unlikely possibilities, e.g., a fault may not occur due to construction equipment bumping into the lines in stormy weather; sleet jump or galloping cannot occur in any season other than winter; faults by tree contact cannot occur in an area without trees. To some extent this makes it possible for the ES to narrow the scope of possible causes of the fault.

An ANN is able to build casual relations that cannot be described with specific rules by learning the past fault data. Since the ANN is not badly affected by an input data loss, a satisfactory solution can be obtained even if oscillography data is lacking during a network disturbance. To get accurate data while reducing the learning time, an ANN for each fault cause is built as shown in Fig. 2. For example, the ANN for lightning strike faults learns all past fault data as they are classified belonging to the lightning strike cause or not. If the actual information is entered, the ANN calculates the possibility of the fault being a lightning strike or not.

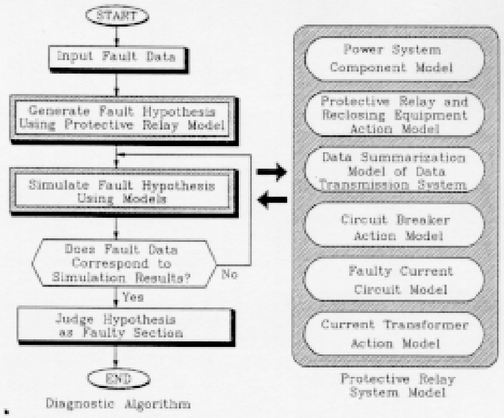

Fig. 1. Diagnostic Algorithm and Model Structure

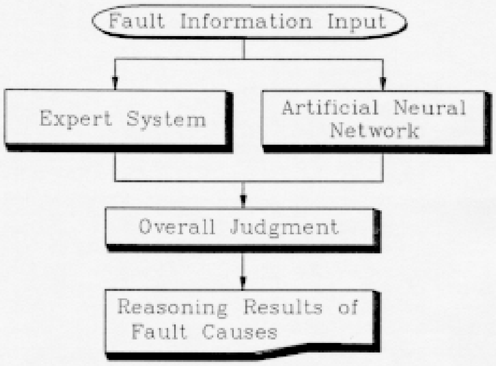

Fig. 2. Processing Flow of Fault Cause Estimation

For an outage where a supply fault remains after restoration, a restoration search procedure is formulated on an operator's demand. Different steps follow a restoration search, depending on whether or not restoration is executed for an operation fault at a given step. Therefore, when an operator demands formulation, the succeeding energizing search procedure is automatically made, based on post–operation system status data obtained via an EMS each time an operator executes a restoration search operation. These processes are repeated by applying the transmission line and substation fault restoration search knowledge. This application was tested with an operator training simulator as shown in Fig. 3. When a restoration operation (including the selection of a restoration search circuit breaker, isolation of outage blocks, and load switching) corresponds to the restoration search procedures issued by a trainee using a system operation simulator, it is judged correct. If not, causes for discrepancies and countermeasures are examined by investigating the restoration operation from the point at which the discrepancies begin to appear, and the restoration search knowledge which includes the restoration operation is modified [3].

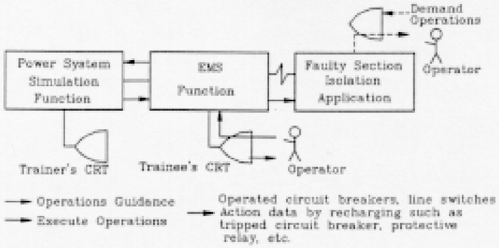

Fig. 3. Testing System for a Fault Section Isolation Application

Lessons Learned and Future Trend

A diagnostic shell that reflects and makes use of the nature of model-based diagnosis of discrete event systems has been developed to overcome the difficulties explained above, and has obtained good results for simulated power systems. For applying it to a future EMS application, the more detailed protective relay models considering numerical network analysis have been studied to improve fault section detection performance.

During a half year field use, about 20 network faults at a transmission line have been experienced up to now, and all of the faulty causes were estimated correctly. The future study of this area include a learning method of cause estimation for faults in a substation that have rarely occurred in the past and an automatic communication method for transmitting the oscillography data to an EMS.

Using the testing system described above, the fault restoration knowledge has been revised. And based on it, currently implementation issues such as interactive data representation method for the operator, and smart knowledge representation are being studied with power utility staff toward a practical use.

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FAULT DIAGNOSIS IN THE ON–LINE ENVIRONMENT

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Power system faults can occur on transmission lines, machines, transformers or busbars. Relays and circuit breakers are designed to clear faults. Communication devices transmit analog and status data from substations or other monitored points to the control center. Events such as breaker operations are detected through a Supervisory Control and Data Acquisition (SCADA) system which monitors the state of the power system. The Energy Management System (EMS) analyzes the power system data and reports the system state to power dispatchers. The purpose of the *on–line* fault diagnosis task is to identify the fault location(s), type(s), malfunctioning devices, and their cause–effect relationships from the EMS information and any other available sources of information.

When a fault occurs, protective devices are designed to isolate the fault so that the impact of the fault can be minimized. However, the protective devices, including relays and breakers can malfunction. Relays can malfunction in different ways, e.g., sending a tripping signal when they are not supposed to, or not sending a tripping signal when they should. The operating time of a relay can also be incorrect which may cause unnecessary outages; for example, a relay may trip before the setting time, not giving relays closer to the fault sufficient time to operate or a relay may delay its tripping signal longer than its setting time.

Fault diagnosis for power systems can be done at the device, substation, and control center level. At the device level, attempts are made to identify the failure mode of specific devices such as transformers or generators. At the control center level, the location and characteristics of the fault are inferred from data acquired on–line and possibly other sources. When information is lost (e.g., a failure of the communication system), a definitive conclusion about the location, or cause of the fault, may not be possible.

Depending on the extent to which the system is monitored, the method of fault diagnosis may be different. Based on the level of details, monitoring of the protective devices (i.e., relays and breakers) in the control center environment can be divided into three classes: (1) only breaker operations are reported to the control center, (2) both breaker and relay operations are reported to the control center, and (3) breaker and relay actions collected by Sequence–of–Events Recorders (SERs) are communicated to the control center. In the control center, the level of accuracy of fault diagnosis depends on the amount of information available on–line.

When only breaker status is available, a faulted region isolated by open breakers may be identified which contains the faulted device. Using the information on breaker operations, it is also possible to determine some fault characteristics, e.g., temporary or permanent. The de–energized region contains lines, transformers and/or busbars that may be faulted. Busbars and transformers are usually protected by differential relays while distance relays are common for transmission lines. It may be easy to identify a busbar/transformer fault based on the differential protective scheme. However, with only breaker information, it may be difficult to pinpoint the specific line that is faulted within the de–energized region. Additional sources of information may be available, such as information about automatic switching or reclosures, which may be used to limit the number of potential faulted sections [1]. For complex scenarios, a fault diagnosis system with only breaker information may have to hypothesize many fault scenarios. When the number of hypotheses is large, the effectiveness of the fault diagnosis tool is low.

If relay information is collected along with the breaker status data, the information may be used to more precisely locate the faulted power system element and to identify characteristics of the fault (e.g., single or multiple phases faulted). Additionally, with the availability of relay information, it is possible to determine if a breaker has malfunctioned. If SERs are used to collect precise timing information (within msec) for relay and breaker operations, in addition to being able to better determine the location of a fault, malfunctions of relays and/or breakers can be detected [2].

The analysis of power system data for fault analysis can be based on logic or on device/system models. When a set of protective device operations are analyzed, the location of the fault can be logically deduced based on topological, physical, and behavioral relations. Another approach to fault diagnosis compares the recorded operation of devices and other measurements to models of the devices and the system. From this comparison, faults are identified which could have caused the observed data. For example, if the gathered data indicates that pilot tones were received for both relays on a line, then the relays operated for a zone 1 fault which must be on the line between the relays.

As advances in communication and computer systems make it more economical to collect increasing amounts of data, more data may be reported to the power system control center in the future. The increased amount of data will likely contain redundant information and increase the amount of time and effort required for dispatchers to make decisions. With the introduction of automatic fault analysis applications, the increased quantity of data can be analyzed and the results presented to the dispatchers in a more accurate and concise form.

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James Waight has a BSEE and MBA from Marquette University, and a MSEE from the University of Minnesota. He has a total of seventeen years of experience in the development, delivery, and marketing of EMS systems. He is currently the Manager of Operations Planning at Siemens Empros. He is a Senior Member of the IEEE and a Registered Professional Engineer in the State of Minnesota.

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