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Fault Analysis Using Intelligent Systems

Four IEEE Power Engineering Society (PES) subcommittees or working groups are presently concerned with intelligent system applications and are coordinating their activities. A joint panel session on fault analysis was held during the 1996 IEEE PES Winter Meeting in Baltimore, organized by:

- M. Kezunovic, panel chair and moderator (Power System Relaying Committee)
- C.C. Liu (Power Engineering Committee)
- S.S. Venkata (Transmission and Distribution Committee)
- R. Adapa (Energy Development and Power Generation Committee).

Applications of expert systems, neural networks, fuzzy logic, and genetic algorithms are helping utilities reach their fault analysis goals and objectives

The panel session dealt with various aspects of the specification, design, development, and application of different solutions for automated fault analysis using advanced intelligent system techniques and tools. In order to provide an overview of a variety of issues associated with the fault analysis automation, the panel was formed of experts from the utilities, vendors, and academia. The utility representatives (Rede Electrica Nacional, Portugal; Houston Lighting & Power Company, United States; Electricite de France, France) presented requirements and application experiences for the transmission, distribution and power plant applications. The vendor representatives (Siemens, United States; Mitsubishi, Japan) offered their view on advanced concepts for the solutions and related products. A representative of academia (University of Washington, United States) gave a perspective of some future trends in this field.

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Fault Analysis Automation

M. Kezunovic, Texas A&M University

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 alarms associated with faults
- Analysis of the operation of protective relays and associated switching equipment
- Identification of the faulted section
- Location of faults
- Determination of the power system switching state after the protective relay operation.

The ultimate interpretation of the term and associated applications comes from 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, and engineering design staff.

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

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 systems, neural nets, fuzzy logic, and genetic algorithms.

About the Moderator

Mladen Kezunovic received his Dipl. Ing. degree from the University of Sarajevo, Yugoslavia, MS and PhD degrees from the University of Kansas, all in electrical engineering in 1974, 1977, and 1980, respectively. His industrial experience is with Westinghouse Electric Corporation in the United States, and the Energoinvest Company in Yugoslavia. He also worked at the University of Sarajevo, Yugoslavia. He was a visiting associate professor at Washington State University and at Texas A&M University, for the 1986-1987 and 1987-1989 academic years, respectively. He is presently a professor at Texas A&M University. He is chair of the IEEE Power System Relaying Committee

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working group on Applications of Intelligent Systems to Protection Engineering. He is a Senior Member of the IEEE, Member of CIGRE, and a registered professional engineer in Texas.

REN Applications for Incident Analysis and Maintenance Management

M.F. Fernandes, Rede Electrica Nacional

Rede Electrica 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.

Incentives for the Applications

To monitor and control the transmission grid, 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.

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.

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.

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.

About the Speaker

M. Fernandes was born in Lisbon, Portugal. She received a diploma in electrical engineering in 1975 from the Technical University of Lisbon (IST) and a diploma in computer engineering in 1977 from University Nova de Lisboa (UNL). From 1975 to 1979, she lectured on digital systems and data communications at both universities. Since 1979, she has worked at Electricidade de Portugal (EDP), first in the Transmission Substation Automation department as a project engineer involved in several real-time automation and control projects, and as the head of the department since 1988. Presently, she heads the Control and Protection Systems department at REN (Grupo EDP). She participated in ESPRIT "DIAS" and BRITE "AMPERIO" projects (both sponsored by the EC) and was a member of the CIGRE TF 38-06-05 on Applications of Expert Systems to Education/Training of Power System Engineers. She is a member of the CIGRE Study Committee 35 WG01 on Control Centres.

HL&P Applications

D.R. Sevcik, Houston Lighting & Power Company

Houston Lighting and Power (HL&P) uses intelligent systems for fault analysis and is pursuing the use of a real-time expert system in a generator application.

345 kV Substation Application

A common practice at HL&P 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 and developed as a possible solution to this problem.

The expert system was installed at the South Texas Project switchyard. 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 at HL&P to collect power plant generator disturbance and fault data by DFRs. Based on the favorable experiences obtained from the transmission DFRs and expert system, a power plant generator application utilizing a new DFR and real-time expert system is being pursued.

The initial set of expert system application functions that will be implemented are:

- Voltage unbalances
- Current unbalances
- Excessive V/Hz detection
- Negative sequence current detection
- Loss of field detection
- 100 percent 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.

The system was installed and commissioned in 1996.

About the Speaker

Donald R. Sevcik received his BSEE from Texas A&M University in 1975. He has been employed by Houston Lighting & Power Company since 1975 and is currently a lead engineer. He has worked in the following areas: Power Plant Electrical System (1975 to 1977), System Studies (1977 to 1979), and Transmission and Generation Protection (1979 to present). He is a Member of the IEEE and a registered professional engineer in Texas.

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EDF Applications at Power Plants, Substations, and DMS

A. Hertz, Electricite de France

Work in artificial intelligence began at Electricite de France (EDF) about 10 years ago. Many projects were launched, but few remain, most in the diagnosis and fault analysis field. The main applications are in power plants, at the substation level, and at 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 first system was installed in a French nuclear power plant. The second direction leads to the definition of diagnostic systems which propose an interpretation of observations.

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.

Maintenance Applications at the Substation Level

Two systems allowing analysis of data recorded in substations during incidents mainly for maintenance purposes have been developed.

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 occur on the network.

What is the motivation behind the distribution system application? EDF has developed a method, named *auscultation*, which consists of analyzing all the electrical incidents affecting a distribution feeder and identifying the sources of transient faults. Feeder *auscultation* uses two types of equipment:

- A fault recorder, installed at the HV/MV substations, recording voltages, currents and logical information from the protection system
- Fault detectors installed along the feeders, noting faults (time-stamped) on the downstream portion of the network.

Incident Analysis and Restoration at the Distribution Dispatching Level

This application is still under development. Part of this new development is devoted to restorative control after an 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.

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.

About the Speaker

Arnaud Hertz received his civil engineering degree from ENPC in 1972 and PhD in the artificial intelligence field from PARIS VI University in 1975. He entered the EDF R&D department as a research engineer in 1976 and developed operational-research software for the planning of electrical networks. Between 1987 and 1992, he lead a team of twelve engineers and researchers dealing with the application of artificial intelligence techniques and new algorithmic methods for power system problems. He is involved in coordinating groups in the EDF R&D Department about software engineering and artificial intelligence. He is presently the scientific advisor in the power system branch of the R&D department for various computer related matters: software engineering, artificial intelligence, control centers, and substation system architectures. He is a Member of the IEEE, CIGRE, ACM, Council of the Department of Computer Science at PARIS VI University.

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Knowledge-Based Location of Transmission System Faults

James Waight, Siemens Empros Power Systems Control

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 (e.g., the presence of multiple faults) or the misoperation of protection 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.

FDS Design and Structure

The Fault Diagnosis System (FDS) has been developed, and it is activated whenever the SCADA system detects a relay operation in the network. 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.

Diagnosing systems faults requires data about the network, the protection system, as well as the real-time status of breakers and relays. Since FDS is intended for unassisted, online 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 that have operated. The distance relays are classified according to signal type as primary, high impedance, and ground.

Experience and Results

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.

About the Speaker

James Waight has a BSEE and MBA from Marquette University, and a MSEE from the University of Minnesota. He has 17 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 Minnesota.

Fault Diagnosis for Power System Restoration

Shinta Fukui, Mitsubishi Electric Corporation

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:

- Faulty section detection
- Fault cause estimation
- Faulty section isolation.

Lessons Learned and Future Trends

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, 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 6 months of 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. Future studies in 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 this testing system, 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.

About the Speaker

Shinta Fukui received his BSEE from the University of Tokyo, Tokyo, Japan, in 1980. He joined Mitsubishi Electric Corporation in 1980. He has been involved in the development of power network analysis and artificial intelligence applications. Currently, he is an assistant manager, responsible for the area of advanced technology in power systems planning and operation. He is a member of the Institute of Electrical Engineers in Japan and of the Information Processing Society in Japan.

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Fault Diagnosis in the Online Environment

Chen-Ching Liu, University of Washington

The purpose of the online fault diagnosis task is to identify the fault locations, types, malfunctioning devices, and their cause/effect relationships from the EMS information and any other available sources of information.

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 online.

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.

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.

About the Speaker

Chen-Ching Liu received his BS and MS degrees from National Taiwan University and the PhD degree from the University of California, Berkeley. Since 1983 he has been with the University of Washington, where he is professor of electrical engineering. During 1994-95, he was program director for power systems at the National Science Foundation (NSF) of the U.S. Federal Government. He was elected "Teacher of the Year" by electrical engineering students at University of Washington in 1985. He received a Presidential Young Investigator Award from NSF in 1987. He was recognized for supervising a student paper that was awarded the 1994 PES T. Burke Hayes Paper Prize. He was guest editor of the May 1992 Special Issue of Proceedings of the IEEE on Knowledge-Based Systems in Power Systems. He is chairing the Intelligent System Applications working group of the Power System Engineering Committee. He has been a member of the Power Engineering Society Governing Board since 1992; he is a Fellow of the IEEE.