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Potential Applications of Expert Systems to Power System Protection

Working Group D10 of the Line Protection Subcommittee, Power System Relaying Committee
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Abstract

Working Group D10 *Applications of Expert Systems to Power System Protection* of the Line Protection Subcommittee, Power System Relaying Committee, was organized in 1989 with the following assignment as finally adopted:

> Survey expert system technology to identify suitable and significant applications to power system protection. Write a technical paper that introduces protection engineers to expert systems and describes several potential applications.

This paper represents the work performed by the Working Group in fulfilling its assignment.

The paper is divided into sections that describe a number of potential applications thought to be significant by the members of the Working Group.

1 Introduction and Overview

1.1 Artificial Intelligence

Artificial Intelligence (AI) is a technology that has been revitalized in recent years, although it has been a part of computer science and applications since the early days of digital computers. One simple view of the field is that it is concerned with devising computer programs to make computers smarter; computers make decisions in the way human beings do, with reasoning analysis. The basic elements composing an AI program are

- modeling and knowledge representation,
- common-sense reasoning and logic,
- languages and tools, and
- heuristic search [1, 2].

AI sub-disciplines can be broadly classified as: Expert Systems (ES) [3, 4, 5], Knowledge-Based Systems (KBS) [5], Intelligent Decision Support Systems (IDSS) [5, 6], Artificial Neural Networks (ANN) [7], Smart Robots, Machine Vision, Natural Language Processing, and Problem Solving and Planning. The evolution of successful expert systems such as MYCIN for medical diagnosis, R1 for configuring computers, and DENDRAL for chemical analysis in the 1970s rejuvenated the field of AI.

Recognizing these successes, power engineers were motivated to investigate the application of ES to power system problems during the 1980s [8]. Most of this work was directed towards the development of expert systems as an operator's aid in power control centers for transmission systems operating under abnormal conditions [9]. Alarm processing, fault diagnosis, system restoration, and reactive power/voltage control are a few key areas in which significant work has progressed to date [10]. An extensive bibliography of expert system applications was published in 1989 [8]. A special issue of the *Proceedings of the IEEE* [11] contains 11 recent papers on applications of expert systems to power systems. More than one hundred prototype expert systems have been developed in the United States, Japan, and Europe [12, 13, 14].

Application of ES to power system protection has also been investigated for several years, but very few applications have been implemented owing to the

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stringent time response requirements of relaying functions [15]. Most existing applications are to problems for which this time response requirement is not critical such as relay setting and coordination, high-impedance fault detection, fault location, substation fault diagnosis, and power transformer fault diagnosis [16]–, [20].

1.2 AI Techniques

This section provides a brief introduction to several AI techniques so as to set expert systems in its more general context. It is presented at a very elementary level to assist in the orientation of engineers entirely new to this discipline. Expert systems themselves are characterized as well as the other AI techniques.

Besides Expert Systems, power engineers have also recently been investigating the application of other AI techniques such as KBS, ANN, and IDSS to power problems. Although they have certain similarities, each of these methods may be used as a vehicle for different problem-solving strategies. Furthermore, each of the above mentioned methodologies has its strengths and weaknesses. There are some power system problems such as protection that are not easy to define, formulate, or structure for conventional automated (computerized) methods only. These problems are characterized by [21]:

1. the absence of a predetermined decision path from the initial state to the goal (ill-structured problem) or
2. a lack of well-defined criteria as to whether a solution is acceptable (open-ended problem).

For these complex problems, conventional overall computerized tools do not yet exist. Recent developments in AI, particularly in knowledge engineering, can be used to broaden the scope of the computer-aided protection domain. Before proceeding further, the AI methodologies introduced above will be briefly described [21].

Expert Systems

An expert system (ES) is a computer program that uses knowledge and inference procedures to solve problems that are ordinarily solved through human expertise. A "knowledge engineer" obtains the necessary knowledge from a human expert and puts it into a "knowledge base." This knowledge together with the inference procedures used can be thought of as a model of an expert in a specialized field or domain of interest. The basic components of an ES are:

- knowledge base,
- inference engine,
- data base, and
- user interface.

From a programming point of view, expert systems are based on the rule-based programming paradigm. The problem-solving control strategies employed by expert systems are forward chaining, backward chaining, or a combination of the two. A forward chaining inferencing control strategy is intrinsic to planning and configuring problems, whereas backward chaining is well suited to diagnostics.

Knowledge-Based Systems

Expert systems basically mimic the problem-solving behavior of experts using domain knowledge acquired during the knowledge acquisition process. Knowledge-based systems go beyond that in the sense that they enrich problem-solving strategy with methods that are not originally employed by human experts. Systems that use domain knowledge to guide searches in ways that differ from the expert's are known as Knowledge-Based Systems (KBS). The problem-solving control structure of a KBS is more advanced and usually employs "knowledge about knowledge" or "metaknowledge" for guiding the overall solution process. Blackboard systems [22] and agenda-based systems [23] are the two most frequently used types of KBS architectures.

Intelligent Decision Support Systems

Decision Support Systems (DSS) are computerized tools derived from decision theory used to enhance user ability to make decisions efficiently. They are not intended to offer the final solution, but rather to explore and seek alternative solutions. The ultimate decision is left to the user. They are well suited to open-ended problems and are mainly employed in planning. Conventional decision-support systems are used for retrieving, manipulating, or summarizing data in a way that assists decision makers. Some common decision-support systems are spreadsheets and data base management systems.

Intelligent Decision Support Systems (IDSS) add intelligence to existing systems to enhance problem-solving ability and help maintain a broad range of knowledge about a particular domain. They are used for capturing, organizing, and reapplying knowledge including decision rules and criteria.

Artificial Neural Networks

The emerging technology of Artificial Neural Networks (ANN), which simulate the neural activity of the human brain, deserves recognition at the same level as the AI methodologies mentioned above. ANN have already been broadly classified under the AI domain; they do not have some of the properties of AI, but can be placed under the umbrella of AI technologies.

1.3 Contents of the Paper

The main body of this paper consists of six sections that contain brief descriptions of the following protection problems:

- Protection equipment failure and event diagnosis
- Protection selection, setting, and coordination
- Fault identification and Location
- Service restoration and remedial action
- Distribution feeder protection
- Solar magnetic disturbances

The descriptions are limited to problem statements; no attempt is made to provide solutions. The intention is that these problem descriptions will motivate solution providers to devise solutions using expert systems or other applicable technology.

2 Protection Equipment Failure and Event Diagnosis

The goal is to utilize information gained from the operation—either correct or incorrect—of a protective relay system. This information would be used to provide system operators a better basis for operation of the system. The rules could be derived from experience, relay system reference books, intelligent relay systems, and system "pre" and "post" conditions.

2.1 Failure Diagnosis

The expert system for this application could be divided into two categories:

1. those of benefit to the user immediately after the occurrence and
2. those of benefit after an extended period of time.

Potentially, system operators would likely be the main users of the immediate information. Maintenance personnel and system planners would typically utilize more detailed information, which could be gathered over longer periods of time.

Standard modules would have to be customized for different utility systems and specific user requirements. Also, different practices are utilized at different voltage levels. The system could be categorized according to distribution, subtransmission, and bulk transmission.

The expert systems would essentially be able to analyze an occurrence on the system and make a recommendation as to a course of action. In many ways, the expert system would parallel the protective relay system itself. The significant difference is that the relay has a small number of parameters on which to base a decision in a relatively short period of time; with an expert system, there are fewer limitations in terms of the number of measurement parameters or length of time required for a decision.

The system must have an ability to recognize typical failure modes of various protective schemes. Three distinct areas for analysis would be:

1. internal relay equipment failure,
2. external equipment failure, or
3. human failure in design or setting.

The expert system would distinguish between the several failure modes. After this distinction had been made, another set of criteria could be used to arrive at an appropriate course of action.

Another feature desirable in such a system is the ability to learn from previous experience. If a given situation occurred more than once, the experience could be used to choose a course of action for future occurrences or to modify the probabilities assigned to different diagnoses.

2.2 Event Diagnosis

An "event" could be a failure, but could also be a fault, equipment failure, abnormal voltages or currents, or even a desirable but incorrect operation.

For this application, the "expert" is placed in the control house of a substation. All of the information within that control house is made available to this expert: relay operations, equipment status, alarm status, sequence-of-events data, analog levels of station parameters, fault recorder data, etc. The expert system is "taught" which of these inputs to expect for each failure.

The expert system would assign probabilities to its diagnoses. The more information available and the less conflict within the information, the higher the probability assigned. If a lot of data are available to the "expert," accurate results will be easy to obtain. For example, if relay targets, sequence-of-events, fault data, and equipment status are all known, and if the information is consistent, most events will be easily identified as line faults, bus faults, or whatever kinds of faults they may be. However, if data are limited or in conflict, as is often the case, the expert system will have to rely on probabilities to provide analysis.

The expert system's diagnosis could be communicated to a control center over SCADA to assist operators in making decisions regarding restoration or the dispatch of personnel. Rather than being deluged with unprocessed information on equipment status, alarms, etc., the operator would be fed an analysis of probable failure or event and, if appropriate, could also be provided with suggested actions.

2.3 Guidance for Preventive Maintenance

Suppose a failure is detected and reported. The failure could be detected by misoperation, failure to operate, monitoring equipment, preventive maintenance, etc. The failed equipment or component must have an identification code that not only identifies the component, but also links it to the equipment and systems in which it is an integral part. For example, a failed capacitor may be identified simply as a "capacitor," but may also be classified as

- a component of a relay,
- a component of a primary relay system, or
- a component of a line protection terminal.

The failure is entered into the ES data base. The expert system checks the failure history of the component, taking into account the total number of components. The resulting failure statistic would then be multiplied by a failure consequence, which would be a part of the data base for each piece of equipment. If this result exceeds a certain level, equipment or systems would be flagged for maintenance.

Productivity gains could be realized by using an expert system for the administration of a scheduled preventive maintenance program for protective relaying equipment. The knowledge base would include the required scheduled maintenance along with the results of past maintenance, the importance of the equipment, and the available man-hours. The expert system would then determine the list of components to be maintained for the given time period.

The expert system would also need to provide the services of an experienced repair supervisor. When a problem occurs, the expert system would look at both the history of the equipment and a library of solutions from the manufacturer to determine the corrective action to be taken. The most likely solutions would be presented to the relay technician. The technician would then feed back the actual corrective action taken so the expert system can "learn" better how to handle future occurrences.

Following are some example steps the system would need to go through to process and categorize the maintenance information:

- What is the maintenance category of the equipment?
- For what relay type or control scheme function was the maintenance performed?
- In what subcomponent does the problem exist?
- How long has it been since this equipment was last maintained?
- Was there a problem?
- Has the problem occurred before?
- Report to the technician the problems of this nature that have occurred in the past. This information would include repair solutions that will have been stored in the system by the manufacturer of the equipment.

After performing maintenance, the relay technician would download the maintenance information into the office expert system for that work area. Upon request, this computer would respond to a master station that would in turn teach the office system and the technician's computer what has happened throughout the system. The master station would then maintain statistics and provide future maintenance schedules and assignments.

The expert system would have the ability to learn from experienced maintenance and repair technicians and supervisors. Systems such as this would lessen the impact of early retirements on the effectiveness of an organization. Expertise could be maintained even longer than the average working career of the experienced technician.

In the future, much preventive maintenance may be replaced by maintenance on demand, as is now often done for cars, airplanes, and other systems of some complexity. Expert systems may be used to analyze the "demands."

3 Protection Selection, Setting, and Coordination

A coordinated protection system is a basic requirement for reliable transmission and distribution capability. The configuration of a power system may change hourly or more often owing to weather, maintenance, malfunctioning equipment, or other outage-causing events; over a longer time the configuration is changed by new construction, re-conductoring, and long-term outages. Also, the nature of protection coordination (particularly backup protection) requires study and planning at the *system* level. If a system plan fails to include fully integrated protection solutions, a utility could face continuing operational problems.

There are at least two levels on which expert systems can aid in the selection, setting, and coordination of protective systems:

1. global, integrated protection planning through general rules and
2. resolution of conflicts where general rules are inappropriate or provide unsatisfactory protection.

The expert system for integrated protection should begin with a detailed description of protection objectives, developed in cooperation with system planners. A major benefit of developing an expert system may be in clarifying the performance requirements and objectives of the protective system. Planning in this context includes operations, with its attendant maintenance and environmental requirements.

Routine setting and coordination of relays on a system-wide basis is an immense and complex task. However, it usually reduces to rather simple rules that reflect the general protection philosophy of a given utility. Although this is primarily an algorithmic process, the expert system application operates at a higher level in providing the rules and guiding the routine algorithmic application of the rules.

In applying general rules for setting and coordination, the protection engineer inevitably runs into situations that do not fit the rules. In such instances, he must permit miscoordination or make other compromises. An expert system applied at this lower level would be especially useful in solving these difficult and unusual cases. The role of the human expert then becomes one of defining weighting factors and devising rules for resolving conflicts rather than selecting among specific solutions.

The multitude of setting and application options afforded by modern digital relays poses a problem of a different sort. An expert system would be useful in helping the protection engineer make the proper selections and settings required for specific applications.

The expert systems developed to address the protection selection, setting, and coordination requirements of the areas listed below should form an integrated whole. Expert systems concepts provide an opportunity to bring the entire protective system into a unified conceptual relationship. In contrast, the traditional approach individually determines relaying requirements for lines, transformers, buses, etc.

3.1 Protection Selection

The initial step in this process would be to determine the type of protection needed and then to select appropriate protective devices. This procedure should consider such requirements as speed, selectivity, reliability, and cost. Standards and application guides could establish the basic rules, but the expert system would need to cover special situations such as compatibility of new equipment with existing equipment and the required input sources for the selected relays.

The protection requirements and practices for different types of equipment and protective functions are diverse enough that each type of protected equipment would require a different set of rules. The equipment types include

1. transmission lines
2. buses
3. transformers
4. generators
5. motors
6. capacitors and inductors
7. other elements

The speed requirements for line protection may depend on line rating, operating voltage, stability, sensitivity of load, etc. The output of the expert system would be a report of the equipment needed to give minimal, recommended, and comprehensive protection for the element under consideration.

3.2 Protection Setting

The next task is the setting of the devices selected by the expert system of Section 3.1 above. Much of the knowledge base would be the same, but might include more details on equipment ratings, damage curves, etc. It must be flexible enough to accommodate standards that vary from company to company and the subjectivity of "rules of thumb." The output would be a report of specific device ratings, ranges, and settings.

3.3 Protection Coordination

Protection coordination requires several serial steps. One suggested approach is to first determine the fault conditions critical to evaluating coordination: the fault types, the fault locations, and the system contingencies in effect. The next step is to determine which devices need to coordinate for a given fault. That is, which ones offer primary protection, and which ones are acting in a backup mode for the given fault? The knowledge base would need data on system topology and device locations and characteristics. The expert system would have to call on an algorithmic procedure to determine device operating times for these critical faults. A final step would look for possible corrective actions when a mis-coordination occurs between devices for a particular fault. Some alternatives might be to change the device's pickup, reach, or timer, or possibly even to upgrade the protective device. In the last case it would be necessary to return to the selection step.

In some protection coordination situations, human experts have differing opinions on the correct action to take. In such cases, it would be desirable for the expert system to report alternative solutions.

4 Fault Identification and Location

In this section we identify opportunities for improving protective relaying by combining expert systems with accurate fault identification and location.

4.1 Benefits of Accurate Fault Location

It would be possible to improve the protection afforded by relaying systems if the type of fault or cause (e.g. contamination, lightning) were known and available to an expert system. (Or, another application of an expert system might be to *determine* the type of fault and its cause.) A computer-based relaying system could optimize its primary clearing time, reclosing initiation, reclosing time delay, and number of reclosing attempts in response to a particular event. This would allow rapid and permanent removal of faults having a high potential for permanent equipment damage or safety hazard (e.g. crane contact). It would also allow slower primary clearing of fault types likely to become self-clearing. Finally, the chance of successful reclosing could be increased by tailoring the number of shots and associated time delays to the type of fault.

Several manufacturers currently offer digital fault locators; fault location can be made even more precise and reliable by the intelligent comparison of messages from both ends of a line. At least two improvements may evolve through the combination of expert system technology with fault-locating devices:

1. If the accuracy of fault location were good enough and the speed high enough, it could be used in place of pilot systems for high-speed relaying, thus potentially reducing both capital and maintenance costs.
2. It could quickly identify and isolate a permanently faulted line section. This would require networking with the SCADA system for remote control of line sectionalizing switches.

4.2 Operating Principles

It appears that the key to remote fault type identification will be through "signature analysis," wherein the relaying system quickly determines the fault type based on analysis of the transient waveform generated by the fault. Further, it appears that such signature analysis will depend on the use of artificial intelligence. This will allow such systems to "learn" to associate certain waveform characteristics with certain types of faults. This technology may also help to increase the fault locating accuracy of relay systems.

4.3 Potential Barriers

The ability of a system to "learn" from experience appears to be necessary to accomplish the goals discussed here. Additionally, the frequency response of conventional instrument transformers may be inadequate to reproduce the transient waveforms on the secondaries with sufficient accuracy for signature analysis. Optical transducers may provide the needed frequency response.

5 Service Restoration and Remedial Action

Although automatic restoration of service and remedial action schemes are not, strictly speaking, protection items, it is usually the task of protection engineers to specify them. This will involve input from other planning and operation engineers indicating the system requirements.

5.1 Restoration of Service

This task is to determine whether automatic restoration of service (auto-reclose) is required and, if so, whether supervising devices are required. The policies of utilities vary on this topic, with factors such as system stability, effect on customer service level, concern for operator convenience, and cost as examples of what are usually considered. The knowledge base must be flexible enough to allow for different policies by different companies.

Practices and rules could vary between companies, but many utilities apply voltage relays at the "lead end" to detect loss of voltage (to ensure that the far end has cleared) and at the "follow end" to detect restoration of voltage (to ensure that the lead end has reclosed successfully). Other supervision relays, e.g. parallel line presence or synchrocheck, may be required to ensure that the circuit will not close out of synchronism with the system. The selected speed of reclosure will depend on many considerations such as system stability, the presence of tapped transformers with motor-operated disconnects for isolation, and operator convenience.

5.2 Remedial Action

These schemes involve a substantial number of conditions and rules to determine the remedial action required. For example, some utilities have generation shedding facilities that require the operator to arm an amount of generation to be shed based on the system conditions prevailing at a given time. An expert system could replace a look-up table that the system operator has to search to determine what is required. The expert system would establish the amount of generation to be shed and which generators should be armed for shedding, based on the system condition.

6 Distribution Feeder Protection

While many of the considerations in the previous sections apply, there are a number of unique requirements for distribution feeder protection. In order to utilize the expert system to improve relay settings and coordination on a distribution system, the following data should be available:

- Predetermined rules such as:
  1. Minimum time to trip criterion.
  2. Coordination time between the protective devices.
  3. Protective device operation time.
  4. Instantaneous setting criterion.
- Fixed (at a given time) data such as:
  1. System (source) impedance.
  2. Line parameters.
  3. Protective device locations.
  4. Protective device characteristics.
  5. High-side protective device settings.
  6. Distribution transformer impedance and capacity.
  7. Connected load and load characteristics.
- On-line data such as:
  1. Status of the switches.
  2. Status of the interrupting devices.
  3. Peak load.

In general, existing criteria for device settings and coordination within each company can be applied in the expert system. However, by retrieving data from the field and the data bank, more effective device setting and improved coordination can be achieved.

The following considerations apply to phase and ground overcurrent relay settings for distribution feeders:

- The minimum pickup value can be selected on the basis of fault calculation and peak load during field switching (including cold-load pickup).
- The minimum pickup for ground overcurrent relays can be set very low but above maximum unbalance load.
- Some utilities ignore the coordination between the feeder relay and field protective devices during emergency switching as long as the minimum pickup can "see" the end of the line. With an expert system, the lever can be selected to insure that the relay coordinates with the field protective devices.

The criteria for selecting relay settings can also be affected by adaptive relaying capability, which allows relay pickup and time delay settings to be changed automatically based on system operating conditions.

7 Solar Magnetic Disturbances

Solar Magnetic Disturbances (SMD) can induce voltages in the earth's surface. These voltages cause quasi dc currents to flow in the neutral circuit of grounded neutral Y-connected equipment such as transformers. The dc currents produce sufficient unidirectional bias in the transformer flux to result in operation with some degree of asymmetrical saturation. This leads to the generation of harmonics in the voltages. Also, the overfluxing can cause overheating of transformers, shortening their lives, and increased magnetizing var absorption, lowering system voltages. Shunt capacitor banks have a lower impedance for harmonics and can therefore experience an increased current flow owing to the harmonics. All of these effects cause problems for power systems and protective relaying systems.

Expert systems might mitigate the effects of SMD by suggesting changes in protection functions or system operation if a local device or the power control center could be given information on some or all of the following quantities:

- transformer neutral current (including quasi dc and harmonic components)
- transformer acoustical levels
- transformer tertiary current
- transformer var requirement
- transformer gas analysis or temperature
- transformer current harmonic content
- generator current harmonic content
- generator negative-sequence current
- capacitor harmonic current
- capacitor neutral current

Depending on the information gathered, an expert system could recognize the presence of an SMD and assess its impact on the power system. Further, it could suggest to the operator mitigating actions, such as rescheduling power flows, removing connected shunt reactors, and inserting series capacitors (in transformer neutrals). Recognizing an SMD, an expert system could also reorder the sequence of suggested actions on receipt of an alarm. The expert system might also automatically make changes to protection systems to enhance their operation during SMDs. Some possible changes are: converting transformer temperature or gas accumulation alarms to trips, invoking peak-measuring capacitor bank overvoltage protection, and enabling special generator protection.

At the power control center, a power system analysis could be made to determine the effects of removing selected transformers from service or the voltage and var changes that would occur if a nearby capacitor bank would trip.

8 Summary

Protection engineering is the skill and experience (heuristic) of selecting and setting relays and other protective devices to provide maximum sensitivity to faults and other undesirable conditions while maintaining the following objectives [24]:

Reliability: Correct response to a fault or other hazard.

Security: No response in the absence of a fault or other hazard.

Selectivity: Maximum continuity of service with minimum system disconnection.

Speed of operation: Minimum fault clearing time and consequent damage.

Simplicity: Minimum protective system complexity.

Economics: Maximum protection for minimum cost, including the cost of service outages.

Today, protection coordination is a design and planning problem rather than an operational problem. Electromechanical relays, which still predominate in power systems, do not have provision for remote setting during operation. Their settings are determined for worst-case conditions and cannot usually be changed for different loading conditions or changes in configuration. Because a power system is customer driven, loading of the distribution system components changes with the daily loading curve. In addition, changes in system configuration, which can arise as a result of system restoration or loss minimization, can affect proper setting of protection devices. In that light, protection coordination can be viewed as an operational problem of adaptive protection device setting. Emerging technologies such as digital and microprocessor-based relays will have provision for real-time remote setting and can be employed in adaptive protection coordination. The domain of protection coordination, considered "more an art than a science," involves heuristics and experience and is well suited for the expert system or, more generally, AI approach.

The Working Group has chosen a few significant current protection problems for possible solution by the application of expert system methodology. It is our hope that these problem descriptions will inspire industry suppliers to provide solutions, by expert systems or otherwise, to these problems.

References

[1] P. H. Winston, *Artificial Intelligence*. Reading MA: Addison-Wesley Publishing Co., Inc., 1984.

[2] W. Taylor, *What Every Engineer Should Know About Artificial Intelligence*. Cambridge, MA: The MIT Press, 1988.

[3] F. Hayes-Roth et al., ed., *Building Expert Systems.* Reading MA: Addison-Wesley Publishing Company, Inc., 1983.

[4] D. A. Waterman, *A Guide to Expert Systems.* Amsterdam: Addison-Wesley Publishing Company, Inc., 1986.

[5] M. S. Fox, "AI and Expert System Myths, Legends, and Facts," *IEEE Expert*, February 1990.

[6] J. Fiksel and F. Hayes-Roth, "Knowledge Systems for Planning Support," *IEEE Expert*, Fall 1989.

[7] Y. H. Pao, *Adapative Pattern Recognition and Neural Networks.* Reading MA: Addison-Wesley Publishing Company, Inc., 1989.

[8] Z. Zhang, G. Hope, and O. Malik, "Expert Systems in Electric Power Systems—a Bibliographical Survey," *IEEE Transactions on Power Systems*, vol. PWRS-4, pp. 1355–1362, November 1989.

[9] Chen-Ching Liu et al., "Practical Use of Expert Systems in Planning and Operation of Power Systems," Final Report CIGRE Task Force 38-06-03, September 1992.

[10] T. S. Dillon and M. A. Laughton, eds., *Expert System Applications in Power Systems.* United Kingdom: Prentice-Hall, 1990. pages 383–408.

[11] Chen-Ching Liu, ed., "Special Issue on Knowledge-Based Systems in Electric Power Systems," *Proceedings of the IEEE*, vol. 80, May 1992.

[12] *Proceedings of the First Symposium on Expert Systems Application to Power Systems*, (Stockholm/Helsinki), August 1988.

[13] *Proceedings of the Second Symposium on Expert Systems Application to Power Systems*, (Seattle), July 1989.

[14] *Proceedings of the Third Symposium on Expert Systems Application to Power Systems*, (Tokyo/Kobe), April 1991.

[15] M. Kezunovic et al., "Expert System Applications to Protection, Substation Control and Related Monitoring Functions," *Electric Power Systems Research*, vol. 21, pp. 71–86, 1991.

[16] S.J. Lee et al., "PROSET: An Expert System for Protective Relay Setting," in *Proceedings of the IFAC Symposium on Power Systems and Power Plant Control*, (Korea), pp. 1003–1007, August 1989.

[17] C. Kim, B. Don Russell, and Karan Watson, "A Parameter-Based Process for Selecting High Impedance Fault Detection Techniques Using Decision Making Under Incomplete Knowledge," *IEEE Transactions on Power Delivery*, vol. 5, pp. 1314–1320, July 1990.

[18] A. A. Girgis and M. B. Johns, "A Hybrid Expert System for Faulted Section Identification, Fault Type Classification and Selection of Fault Location Algorithms," *IEEE Transactions on Power Delivery*, vol. 4, pp. 978–985, April 1989.

[19] H. Dijk and N. Kema, "Exformer, An Expert System for Transformer Faults Diagnosis," in *Proceedings of the 9th Power Computation Conference*, pp. 715–721, September 1987.

[20] B. Jeyasurya, S. Venkata, S. Vadari, and J. Postforoosh, "Fault Diagnosis Using Substation Computer," *IEEE Transactions on Power Delivery*, vol. 5, pp. 1195–1201, April 1990.

[21] Z. Sumic, *The Concept and Feasibility of Automated Electrical Plat Design via Intelligent Decision Support System Approach.* PhD dissertation, University of Washington, Seattle, Washington, 1990.

[22] H. Penny Nii, "Blackboard Systems: The Blackboard Model of Problem Solving and the Evolution of Blackboard Architectures," *AI Magazine*, pp. 38–53, Summer 1986.

[23] C. Tong, "AI in Engineering Design," *Artificial Intelligence in Engineering*, vol. 2, no. 3, 1987.

[24] G. Rodriguez and P. Rivera, "A Practical Approach to Expert Systems for Safety and Diagnostics," *InTech*, July 1986.