

Expert System Applications to Protection, Substation Control and Related Monitoring Functions

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ABSTRACT

Application of expert systems to power system problems has become an area of strong research interest in the past few years. A number of papers have been published on the subject with an emphasis on applications that relate to the overall power system monitoring, operation and planning. However, less emphasis was placed on protective relaying, substation control and related monitoring functions.

This paper is primarily concerned with the applications that are focused on power system protection, substation operation, and monitoring. It gives both a survey of the present research efforts and a discussion of future possibilities and trends in this area.

1. INTRODUCTION

The recent publication of several very informative papers on expert system applications to power system problems has provided an extensive bibliography [1], a state-of-the-art review [2], and a survey [3] of present research activities. The main emphasis is on the energy management systems (EMS) related applications such as system monitoring, operation and planning. The primary use of these developments is to assist system dispatchers and other operators to perform their daily tasks.

The area of protective relaying, substation control, and power apparatus and system monitoring has been less emphasized, at least as far as the number of published papers would suggest [4]. It is felt that one of the major reasons for this comes from the real-time con-

straints imposed by the applications which require most of the functions to be executed automatically. Use of the expert system approaches in this case is not yet fully understood and appreciated, and hence more research activities are needed to reach further conclusions.

This paper provides discussion of several important application issues related to the use of expert systems in conjunction with the substation equipment operation. Several applications proposed so far are surveyed and some ongoing research activities are reported. Future application areas are also pointed out. The goal of this paper is also to concentrate on the new developments not discussed in the recently published surveys [1-4].

The first part of the paper is devoted to analysis of functional requirements imposed by the relaying, control and monitoring functions. The most common expert system approaches that can be utilized to meet these application requirements are also pointed out in this section. Next, existing expert system implementations are surveyed with an emphasis on the unique design characteristics and expert system features. This survey is concluded by providing a critical overview of the expert system solutions used. Finally, some development activities are analyzed, pointing out directions for further research efforts. An extensive bibliography is given at the end.

2. IMPLEMENTATION CONSTRAINTS

2.1. Functional characteristics

In order to be able to classify the existing expert system applications as well as to

propose some directions for future research, a detailed discussion is needed of the time response, dependability/selectivity and equipment allocation requirements of the protection, control and monitoring functions.

As is well known, there are a number of protection, control and monitoring functions that reside in a substation [5]. The scope of this paper is to cover expert system applications that primarily relate to these functions. The solutions of interest are the ones that may be implemented at either the substation or the remote control location.

2.1.1 Response time

One of the main characteristics for almost all of these functions is a very short response time. This may be related to the reaction time, if the function is a closed-loop real-time control such as protective relaying. On the other hand, this time may be associated with the execution time if an open-loop operator-initiated function such as substation switching is of interest. Finally, the time response may denote the database update time if data acquisition functions such as alarm and status monitoring are considered. A brief overview of the time constraints associated with the main groups of protection, control and monitoring functions is given in Table 1.

Given the state of the art of expert systems, it is unlikely that they could operate in the short time required for protective relaying. However, a protective relay which implements

an expert system can be programmed in such a manner that the expert system recognizes when to turn over the relaying function to an extremely fast operating algorithm. A permissible longer response time would be selected when there has been a more subtle violation of the state limitations.

Expert systems also offer potential for improving system operations by identifying more complex situations which happen slowly (such as the loss of the transmission network). It may be difficult for a human to determine the action needed in time to prevent the loss of a transmission system. On the other hand, an expert system could determine the necessary actions in time to prevent system breakup as the loss of a transmission system happens over tens of seconds or minutes.

2.1.2. Dependability/selectivity

The dependability and selectivity of protective relays describe the ability of the relay to identify events correctly and take action based upon the information available to the relay. The dependability and selectivity of protection relays have been limited in the past by conventional approaches and limitations of the implementation technology. This has been widely recognized as an inability of the relaying scheme to adapt to the changes in the power system operating conditions.

With the advent of microprocessor applications in protective relaying and the parallel development in expert systems, it is now possible

TABLE 1
Time response constraints

Category	Function	Order of response			Type	Operator
		(ms)	(s)	(min)		
Protection	Line	×			Closed-loop	No
	Transformer	×			Closed-loop	No
	Bus	×			Closed-loop	No
	Backup	×			Closed-loop	No
	Out-of-step	×			Closed-loop	No
Control	Switching		×		Open-loop	Yes
	V/VAR control		×		Open-loop	Yes
	Load shedding		×		Open-loop	Yes
	SCADA		×		Open-loop	Yes
Monitoring	SOE			×	Off-line	Yes
	Disturbance rec.			×	Off-line	Yes
	Fault location			×	Off-line	Yes
	Revenue metering			×	Off-line	Yes

to implement protection systems which can analyze data in a more complex fashion and maintain or surpass the high degree of dependability and selectivity previously available with conventional approaches. This ability implies that the circuits and systems which are protected by the new relay designs can be operated at higher loading capacity and higher efficiency and reliability.

2.1.3. Equipment allocation

Another major consideration is related to the equipment allocation. The relaying equipment is located in the switchyard and/or the control house of a substation. This equipment is connected directly to the related power apparatus and exchange of information between different relays is quite limited. The substation control equipment is usually centralized for the entire substation and is implemented using either a dedicated substation computer or a remote terminal unit (RTU) of a supervisory control and data acquisition (SCADA) system. The monitoring equipment may be organized in a number of different ways. One option is the use of dedicated devices such as sequence of events (SOE) recorders and digital fault recorders (DFRs). Another approach is to have substation-wide monitoring using

dedicated computers for alarm and status acquisition and display. Yet another approach is the use of RTUs to bring the monitoring data to the EMS control center.

One of the latest developments for substation application is an integrated control and protection system (ICPS) approach [5,6]. In this case all of the protection, control and monitoring functions are implemented using a distributed processing system which enables close coordination among all of the functions.

A summary of some of the most important equipment implementation approaches and their characteristics is given in Table 2. It may be observed that the different equipment would require different approaches to expert system implementation. The approaches would range from adding the expert system functions in the existing designs to providing an additional computer to carry out the expert system tasks. This would affect the cost of the expert system designs as well as the possibility for hardware/software optimization of the overall design.

Finally, expert system applications may require a brand-new approach to equipment designs which would combine the functions of several existing types of equipment with the addition of some new functions. The ICPS design is an example of such an approach.

TABLE 2
Equipment design approaches

Equipment type	Location	Communicating with:	Operator interaction
Protection relays	Switchyard/ control house	Switchyard/ eng. office	Change of settings
Fault locators	Control house	Switchyard	Settings, local readings
SOE recorders	Control house	Switchyard	Settings, local readings
Digital fault recorders	Control house	Switchyard/ master station	Local/remote readings
RTUs	Control house	Switchyard/ master station	Remote indicat./ remote control
Operator and revenue meters	Control house	Switchyard	Local readings
Control functions (synch. check, V/VAR, blocking)	Switchyard/ control house	Switchyard/ control house	Monitoring/ initiation
Integrated control and protection systems	Switchyard/ control house	Switchyard/ eng. office/ control center	Settings/ monitoring/ control

2.2. Expert system characteristics

Expert systems have been emerging rapidly from laboratory studies into a broad range of industrial and business applications. The market segment for expert systems and their development tools has grown from about U.S. \$9 million in 1982 to an estimated U.S. \$1.8 billion in 1990 [7]. Many have predicted that expert systems will soon be viewed as merely a new, powerful, programming technique which can be integrated into most computer programs.

In general, an expert system is a program that mimics human expertise in a particular, domain-specific decision-making process. These decisions may pertain to functions in control/monitoring, debugging, design, diagnosis, instruction, interpretation, planning, or prediction. The mimicking of human experts should include not only the decision function, but also the ability to reason, or infer, even in the face of uncertain or missing information. The ability to explain to others what the reasoning is, as well as the ability to act in a correct and timely manner should also be included. The contrast between the expert systems and more conventional computer programs is illustrated in Table 3 [8]. With this Table in mind it should be recognized that most current computers base their architecture on the use of conventional programs, not expert systems. This helps to explain why expert systems seem to push the boundaries of computer resources and execution times more than conventional programs.

New hardware and software which address the constraints found in expert system implementation are continuing to be developed. As the demand for these tools rise, their availability and cost is expected to become more practical. Some of the major characteristics of expert systems are reviewed next.

2.2.1. Area of application

In any comparison of computer programs it is important, even obvious, to keep in mind the area of application. This serves as a reminder that even though one tends to discuss expert systems as if they are one lumped group of programs, their different areas of application require great care when the implementations are compared.

2.2.2. Languages

An expert system can be developed utilizing any computer language. Some languages, such as Lisp and Prolog, have features which strongly support the development of expert systems.

These languages were developed for symbolic processing, and commonly rely upon interpreters to interface the language to the actual computer machinery where they are executed. Other languages, such as C, Fortran, and Pascal, have few or no special constructions for symbolic processing, however these special constructions can be developed in these languages. It may be more difficult to develop or modify expert systems in this latter

TABLE 3
Contrast between expert systems and conventional programs

Characteristics	Expert system	Conventional program
Processing type	Symbolic	Numeric
Major operators	Compare, select, sort, match logic sets, context and partitioning, pattern retrieval and recognition	Arithmetic and logic
Program flow	Nondeterministic	Deterministic (procedure flow and termination predictable)
Execution	Dynamic (creation of data structures makes resource allocation difficult)	Static (clear concept of required resources)
Information management	Representation and acquisition of knowledge is challenging	Algorithms usually well defined with well-structured data
System refinement	Continuously open to refinement	Little to no online refinement mechanism

set of languages. However, since they tend to be compiled languages, they will have faster execution times.

2.2.3. Knowledge source

The source of knowledge for an expert system can influence the other characteristics in its design and greatly affect the ease and time of development. The acquisition of the domain-specific knowledge for the expert system can be the most difficult part of the development. In addition, the ability to check the knowledge base for correctness, conciseness, and thoroughness, in other words the verification of the knowledge base, can be very difficult, depending upon the source of knowledge. For example, the source of knowledge could be a set of manuals, a single human expert, or several human experts. The verification of heuristic knowledge in these three examples can be seen as totally different processes.

2.2.4. Knowledge representation

Rules, frames, or logic, the common methods for representing knowledge in an expert system, are discussed in many texts and articles. Acknowledging that a field of engineering has emerged involving the acquisition and representation of knowledge, the tradeoffs between knowledge representations for the knowledge domain can be complex to evaluate. The choice of knowledge representation can have major effects on the development time, cost, performance, and ultimate success of the expert system design. With the importance and non-trivial nature of the actual choice of knowledge representation in mind, a grossly trivial analogy is given here to provide some feeling for the choices being made.

If the knowledge necessary to plan travel routes can be given adequately in a road map of limited dimensions and the necessary facts are road conditions and goals, then a rule-based representation can be ideal. This is not an attempt to trivialize the power of rule-based systems, for often to try to view information beyond the scope of the road map does not really help in the selection of adequate highways. Thus the rules describing roads, connections and current conditions are quite sufficient without getting bogged down in other characteristics such as road construction characteristics, grades, and speed limits.

However, if the rules become extensive or one must venture at times away from the paved highways, a frame-based representation may become advantageous. More relationships, inherited characteristics, and usually options, may be expressed in a frame-based system. (More rules may do the job but the execution times of rule-based systems tend to be more sensitive to the size of the knowledge base than the execution times of frame-based systems [8].) In the analogy with maps, this may be viewed as the difference between a road map and a contour map. Planning a path with contour maps requires that one can view more of the overall relationships since one may not be depending on paved roads.

Finally, if the knowledge of the terrain is only in the form of some major landmark descriptions and locations, one may have no real map to represent it at all. In this case our logic of searching and identifying landmarks, new and old, must take precedence over dependence on previously paved trails. This logic representation may be much slower than the other techniques, depending upon the terrain, but if the maps are too unreliable or nonexistent this may still be the best option.

2.2.5. Inference engines

The discussion of inference strategies involves search direction and pattern. Whatever the knowledge representation chosen, the inference process involves comparing current conditions with the knowledge base. In some problems the best direction is to view the facts and see what kind of conclusions are indicated in the knowledge base. This is forward chaining. In other applications it may be more important to get goals and subgoals and then find or facilitate the facts which support these goals. This is backward chaining. In still other applications, the combination of the two techniques is desirable. In either forward or backward chaining, matches between the current conditions and the knowledge base are searched for. One may choose to study one branch of options as extensively as possible until one succeeds or is forced to abandon this train of thought and move to another branch. This is a depth-first search. On the other hand, it may be more advantageous to study all possible branches in equal depth and only proceed to deeper levels in the more promising branches. This is breadth-first searching.

Again, it may be advantageous to combine, or switch, from one technique to another within a given problem.

2.2.6. Shells

On top of many languages, knowledge representations and inference strategies, empty shells have been developed for expert systems. These shells require only the domain-specific knowledge base to become functional expert systems. Shells usually provide easier user interfacing for the development and execution of an expert system. The tradeoffs are usually in the constraints (expert system characteristics) chosen for a particular shell, and the costs of the shell.

2.2.7. Hardware

Just as any computer language may be used to develop an expert system, any computer may be used for an expert system implementation as well. The performance of the expert system, as of other computer programs, will be greatly affected by the hardware. The following characteristics make expert systems particularly burdensome on the hardware: (1) the extensive use of memory for program storage and execution space; (2) the vast number of memory accesses for the symbolic comparisons and searches. All of this usually represents execution speed bottlenecks. Some special computer architectures have been developed to support languages such as Lisp or Prolog more effectively. However, demand for these special architectures has not been great enough to manufacture them at a cost comparable with conventional architectures. It still seems that more conventional computer architectures will remain in the forefront. However, it does not seem that the architectures will become more tuned to expert system type processing in the future (especially in their memory management capabilities).

3. SURVEY OF THE PRESENT APPLICATIONS

3.1. Functional description

The following discussion is limited to the functions that are in some way or another related to the relaying, control and monitoring of a power system. The main distinction between this survey and some other recent surveys [1 - 3] is that the discussion given here

focuses primarily on the functions that are directly related to the operation of the substation equipment.

3.1.1. Monitoring and diagnosis

As may be expected, the most frequent expert system applications are in this area. It is well recognized that, in general, an expert system is ideally suited for diagnostic function implementation. This impression has been reflected in the power field as well.

One relatively broad area of application is monitoring of the substation equipment and diagnostics of the abnormal regimes of operation. These activities are directly related to prevention of damages that may result from undesirable equipment conditions. Some authors have proposed expert systems for electric machine diagnosis [9, 10]. One solution is called the Vibration Cause Expert and is aimed at identifying mechanical defects [9]. Another solution is based on a number of sensors providing information about different operating parameters of a turbine-generator system [10]. High voltage circuit breaker monitoring is also viewed as a potential application for expert systems. One approach has been developed to monitor HV breaker contacts, oil pressure and pump conditions, and insulation damage in order to diagnose the breaker operational condition [11]. Some authors are also suggesting expert system applications for diagnosis of HVDC systems by monitoring operational conditions of the converters [12, 13]. The problem of monitoring power transformers by analyzing gas characteristics has also been recognized as an expert system application area [14 - 17]. Similar techniques have been suggested for monitoring overall gas insulated substation (GIS) equipment [17, 18].

Another application area that has produced a lot of different expert system solutions is the fault diagnosis area. Owing to the large number of applications already covered in the other survey papers [1 - 3], only the most recent (1989) applications are reported in this paper. Since this is an area where the first systems are already in online operational mode [3, 19], the references published recently reflect the maturity of the considerations. First, several ongoing system implementation activities are reported [20 - 23]. Then, a number of new techniques for the expert system approach are developed [24 - 27]. Finally, some

new implementation concepts are considered, indicating that the substation computer rather than the SCADA master station may be used for the implementation [28, 29].

3.1.2. Substation control

One of the most common control functions in a substation is the switching function. This function is normally carried out by the operators, but it can also be automated. The approaches proposed so far have enabled data validation, execution of switching sequences and final status verification steps to be automated so that the operator is fully assisted in carrying out such a complex task.

Expert system applications have also concentrated on supporting operators in making their decisions more reliable and secure. Several approaches for expert system applications to the switching sequence implementation have been proposed [30 - 32]. The recent approaches have suggested that overall substation operation can be guided by an expert system [33, 34].

One other area of interest for expert system application for substation control purposes is in distribution automation systems. Preliminary results in this field have been reported [35] and initial implementation efforts undertaken in the area of feeder monitoring and protection [36].

3.1.3. Protective relaying and related functions

Owing to the stringent time-response requirements, there are very few applications of expert systems in the implementation of protective relaying functions. The only known application is in the area of high impedance fault detection.

High impedance faults have eluded the application of any conventional techniques for detection. Such faults appear to mimic normal load conditions experienced on a given feeder. Substantial research in recent years [37 - 39] has shown that it is necessary to implement very sophisticated approaches to identifying what with conventional approaches have been seen as very subtle changes. Using expert system techniques, small differences become obvious changes which are unique to the high impedance downed-conductor fault. This approach provides for reliable, accurate and secure detection.

All of the other expert system applications in the protective relaying field are concerned with the functions closely related to relaying rather than with the relaying functions themselves.

One area of interest is the relay setting coordination function. Some preliminary research has been reported in the past [40 - 42], and one of the activities has produced a prototype system [43]. Similar activities for selection and coordination of fuses in an industrial customer environment have also been reported [44].

Yet another application of expert systems is to aid selection of appropriate algorithms for fault location. A hybrid expert system has been proposed to carry out the fault location function using a combination of known fault location algorithms and expert system support for algorithm classification and utilization [45].

Finally, expert systems are also proposed for digital fault recorder (DFR) signal analysis. Some preliminary results indicate that a combination of digital signal processing algorithms and expert system techniques will have to be used to solve this type of fault analysis problem [46, 47].

As a conclusion, it has also been recognized that integrated control and protection systems may benefit from expert system applications. However, only initial considerations have been reported so far [48].

3.2. Implementation characteristics

A survey of the expert system characteristics for the implementations mentioned in the previous section is given in Table 4.

3.2.1. Hardware

As can be seen in Table 4, various levels of PC class microcomputers, higher level workstations and even microcomputers are used. Only one case indicated that specialized hardware for symbolic processing was used. These choices are made in view of many criteria, including: familiarity, availability, and affordability. The use of PC class machines may be introducing development and performance limitations on the expert systems but may be much more practical for the final environment and users of the systems. In addition, the industrial trend is for the PC class machines to become more and more suitable for expert system applications. This is not only due to

TABLE 4
Survey of expert system design characteristics

Function	Ref.	Expert system characteristics			
		Hardware	Software	Knowledge rep.	Inference
Monitoring					
Rotating machines	9	Symbolics	KEE	Rules	Extensive user interface
HV circuit breaker	10	VAX 11/780	Franz Lisp	Rules	PDS Special AI tool
	11		Turbo-Pascal	Rules	Fuzzy sets, local optim.
HVDC converters	12	Dedicated microprocessor	Prolog	Rules, pattern recognition	Hierar. classif., hypoth. match
Power transformers	14	Standard microcomputer	Fortran	Data formats	Bayes' theorem
	15	PC XT		Rules	Fuzzy sets
Substation eqpt.	17	Hitachi	Eureka II	Rules, frames	Interface to 'C' routines
	18	IBM PS/2-80	Goldworks	Frames	Fuzzy sets
GIS equipment	20	IBM PS/2-80	Goldworks	Rules, demonstra- tions, messages	Certainty factors
	22	DEC/V3500	Comm. Lisp Knowl. Craft	Objects, rules	Softech SADT tool
Control					
Substation switching	23	32-bit PC	Comm. Lisp Prolog	Rules	Bidirectional reasonings, best-first search
Substation operation	25	NEC PC-9801	Prolog	Cause-effect network	Marker propagation
	27		OPS 83	Rules	Forward chaining
	29		Turbo-Prolog	Rules	Forward and backward chaining
	30		Prolog	Rules	Best-first search
Protection	31	Apollo DN 3000	Prolog	Rules	Graph theory
	34	DEC VAX 8550	Pascal 'C'	Rules	Graph theory Hybrid expert system
Relay setting coordination	41	VAX 11/785	POP-11	Rules	Use of problem solver
	43	PC/MS DOS	Poplog	Frames	
Backup protection	44	16-bit PC	Prolog Lisp Basic	Rules, frames	Forward chaining
	48	IBM PC	Prolog	Rules	

rapid advances in processors, but also to the predicted introduction of AI coprocessors for PC class machines in the not too distant future. Therefore, a continuation and expansion of the tendency to see many expert systems developed in PC class machines is predicted for the future designs.

3.2.2. Software

The software column of Table 4 shows a split between the choice of a basic language and the reliance upon an expert system shell. The tradeoff on the selection of a shell is usually cost versus ease and time of development. In many instances the shells may not be tailored enough to the application constraints to warrant their use. Most applications were developed using AI languages in contrast to more conventional languages. In applications with stringent execution time constraints, compiled conventional languages, such as Fortran and Pascal, may be advantageous. If there is a lack of familiarity with a language, it is strongly recommended that a further examination of the AI languages should be performed, as they can be extremely advantageous during construction and modification of an expert system. If interfacing to existing programs is of major concern, then many environments exist today which allow the interface of multiple language codes.

3.2.3. Knowledge representation

The knowledge representation is generally rule based. This is appropriate and natural for many of the current applications. Caution should be exercised as new applications and expanded applications are developed. Rules may seem the simplest to implement, but can often result in performance limitations in more complex systems.

3.2.4. Shells

The shell-based systems will tend to have more development aids for user interfaces. Without using the shells, some applications seem to be still developing their interfaces, even though they are reporting success with their decision processes. In some automation and real-time applications the user interface may be used only infrequently and by relatively highly trained experts, thus, fewer user aids need to be provided than in some user intensive applications.

As a final comment on useful information for the expanded development of expert systems, more discussion on the knowledge acquisition process, how the tradeoffs for the expert system characteristics were made, and the inference strategies in the face of uncertain or missing data would be helpful.

4. RESEARCH ACTIVITIES

4.1. Power system applications

This section gives a summary of the research efforts undertaken by the Power System Automation Laboratory at Texas A&M University and the industrial affiliates. Besides the ongoing research, some future directions are also outlined. The future research directions are based on the general trends in the field and represent proposals for what are believed to be the most promising topics for an immediate development effort.

4.1.1. Protective relaying

The ongoing research projects in this area are related to development of new adaptive relaying and incipient fault detection expert system solutions.

Research has been conducted on the use of expert systems as a part of adaptive techniques for standard overcurrent protection on distribution feeders [49]. Typically, ground and phase overcurrent relays on a distribution feeder are set according to the maximum emergency load which that feeder will encounter. However, much of the time actual load values are far below these pickup settings. As a result, there is a substantial loss in detecting faults.

With the application of expert systems to the problem, it is possible to develop an overcurrent relay which adapts to the load levels in a secure manner. The expert systems can accurately identify other events occurring on the feeder in an intelligent manner, to discriminate them from overcurrent faults. Using such an approach it is possible to make substantial improvements in the application of overcurrent relaying on a distribution feeder to detect more low current faults without increasing nuisance outages.

Some of the techniques which have been developed for high impedance fault detection, as mentioned in §3.1.3, are also useful for

identifying incipient, low current conditions. This benefit is particularly applicable in circuits where even a momentary outage or voltage dip caused by an overcurrent fault could result in an expensive loss of a process or other system emergency.

Incipient fault detection is one area where substation functions can be enhanced through the application of expert systems [50]. It has been determined that an expert system approach is meaningful in solving this complicated fault detection problem. The detection of such faults requires the processing of many different variables related to intermittent changes in waveshape and frequency content. To complicate matters, various feeders will often have vastly different 'normal' levels of harmonics and noise conditions. To predict accurately that an incipient fault is present requires a system which can learn the normal state for each feeder and detect when a pattern of abnormalities represents a fault condition. A large number of staged downed-conductor fault tests have provided data for ongoing work in this area. Activity is underway to develop field-hardened hardware which may be used for protection algorithm validation.

4.1.2. Fault diagnosis

As was mentioned in §3, there are a number of different expert system approaches to the problem of fault diagnosis. The most common implementation is to use a SCADA system as a way of collecting the required field equipment contact data to be arranged as the expert system database. Some of the most recent approaches suggest that a substation-based computer may be used to perform the fault diagnosis function [28, 29, 34].

A research project has been initiated to study an implementation framework for the fault diagnosis function. The main goal of this project is to define different expert system implementation approaches based on various types of equipment used to record and collect relevant field data. It is recognized that the expert system approach is heavily dependent on the type of field data collected and on the level of preprocessing performed by the devices that are used for data recording.

One approach suggested for further implementation is a hierarchical expert system approach that utilizes both the alarm and status

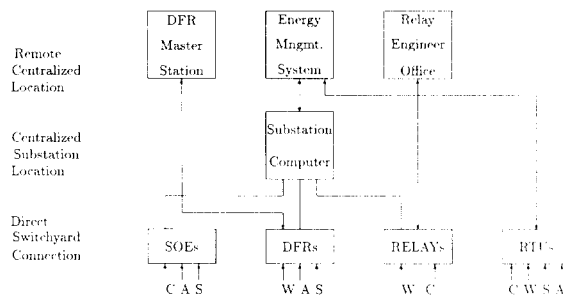


Fig. 1. Hierarchical expert system approach. (C, contact; A, alarm; S, status; W, waveform.)

data recorded by SOE and DFR equipment as well as the analog and contact preprocessed data generated by digital relays. A block diagram of the system is shown Fig. 1. Future research activities will be aimed toward defining the implementation framework based on the available equipment and knowledge related to the interpretation of the system operation using specific data provided by the equipment.

The implementation frameworks identified so far fall into two major categories. One is the individual equipment category where the fault diagnosis is done by implementing expert systems in the individual substation devices. The final conclusion is reached by comparing recommendations given by the individual devices. This is done at a central point where all of the data from different equipment locations are collected and processed. In another category these are the integrated system solutions where various types of equipment are connected to a common database, and the conclusion is made based on these data. Typical implementation examples for the substation level are integrated control and protection systems (ICPSs) [28]. Examples of the new implementation approach for the entire power system are energy management system (EMS) control centers that use ICPS solutions in place of remote terminal units (RTUs) [51].

Preliminary work has also been done on using an expert system to perform fault diagnosis in a distribution automation system [52]. This function involves the determination of the type and location of a fault on a distribution feeder. Such information can be used in several ways, including the provision of information to trouble crews as needed, and potentially to an automatic reconfiguration function for the feeder where this capability is

available. By having fault diagnosis information available to a dispatcher, it is possible to send a trouble crew directly to the point of the fault, thereby saving considerable time and expense over present methods in which the line crew has to drive considerable distances to look for the fault. Where intelligent and controllable switching devices are available on the feeder, it is possible to use the fault diagnosis function to provide a means of automatically reconfiguring circuits in a manner which minimizes the extent of the outage caused by the fault.

4.1.3. Field data recording and analysis

The recent utility practice in the U.S.A. is to install digital fault recorders (DFRs) to capture fault waveforms. The usual approach is to have several DFRs connected to a master station which is located in a central office remote from the substation. A common problem found in most of these applications is the very frequent triggering of the DFRs due to the high sensitivity of the triggering system. As a result, normal deviations are recorded along with the faults and disturbances of interest. Owing to such a large amount of data, the system operators have a hard time going through the recorded events trying to identify the fault events. This is quite an annoying and time-consuming task and produces other problems such as a long transmission time to get all of the records to the central office, and an extensive memory requirement for data storage.

A research activity was initiated under a utility sponsorship to automate the process of classifying and analyzing the fault waveforms. An expert system is being developed to facilitate this task. At present, an 'appended' approach, shown in Fig. 2, is being implemented. This approach assumes that all of the recorded data are transferred to the master station, and then a duplicate of the database is placed

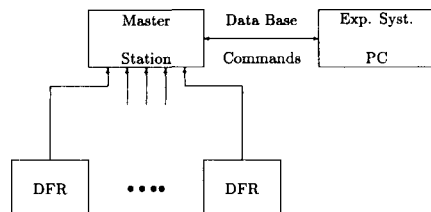


Fig. 2. An 'appended' implementation approach.

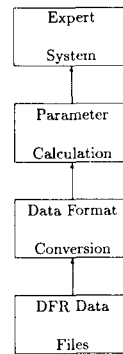


Fig. 3. Expert system functional block diagram.

in a dedicated personal computer which carries out the expert system tasks.

The software functional diagram of the expert system implementation is shown in Fig. 3. As may be observed, the expert system database includes calculated parameters of the recorded waveforms. The calculation of the parameters is the most important step. All of the expert system rules are dependent on the level of information that reflects the parameter change.

Another project in this area is sponsored by a manufacturer. There is currently ongoing work to develop the requirements necessary for future expert system applications in fault recording [47]. Extensive work has led to definitions for parameters which will be necessary to preprocess the massive amounts of data gathered in fault recording. The ability to preprocess and transfer this data in a more timely fashion than available today will be necessary to provide proper information to expert system applications. Areas studied include channel information, sensors, and triggers, as well as other areas which provide substation status information. Methods of ranking individual records created within the substation have been studied as well. This ranking could be used for automatic processing and decisionmaking at a level higher than the fault recorder.

4.1.4. System-wide solutions

This section reports on the expert system implementations that are based on information obtained from the entire power system. Specific proposals are related to the areas of customer load management, integrated substation control and system-wide protective relaying.

Substantial research has been done in recent years on the various means to control customer loads for the purpose of limiting electrical demand. While many of these techniques are relatively unsophisticated, there have been some initial approaches at more intelligent techniques for load control and demand limiting [53]. In one specific area of research, techniques were demonstrated for rearranging load patterns according to regularly scheduled needs. In this demonstration, the air conditioning and kitchen equipment in a fast food restaurant were operated prior to the noon rush hour to precool the building and preheat the ovens. This approach enabled the controller to establish load diversity during the noon rush hour while still responding to load demands. By taking these approaches it is possible to establish some load diversity even during peak use periods so that all large loads are not on at the same time. With an expert system for this application, it is possible for the load controller to develop a history of customer load use patterns. Over time, the expert system can develop techniques for intervening in precooling or preheating certain loads to anticipate certain use patterns. This approach is inherently better because the expert system adapts to the particular use patterns of that customer and will adapt to it over time, as opposed to the technique of programming times for the load controller to intervene.

A load management scheme can also be lumped with the incipient fault detection solution to enable full load management under normal and fault conditions. In this case it is desirable to develop a system which can detect incipient faults and reconfigure circuits to critical loads so that service for these critical loads is rerouted before an overcurrent fault occurs. An expert system can perform such fault detection and load reconfiguration functions in an effective manner. In this way, overall reliability to critical loads can be improved with the potential for substantial savings in cost by avoiding process downtime.

Another research activity has been proposed in the area of substation automation. As a result, several computer system architectures are under development for use in sophisticated control. EPRI sponsored work has led to a recommendation for a communication interface specification for use in control and

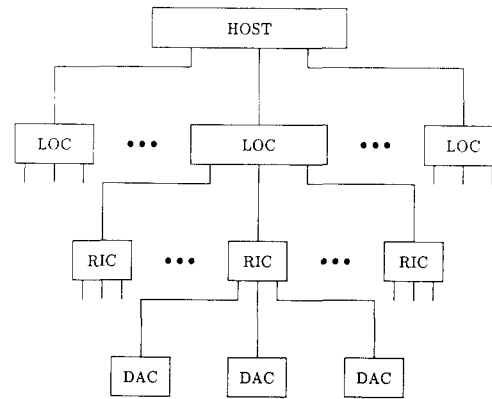


Fig. 4. Automation system architecture: HOST, main computer; LOC, local operating center; RIC, remote intelligent controller; DAC, data acquisition and command.

protection applications, for instance. Work in this area will provide the system tools necessary to implement future expert system applications in control.

Other work provides for the power system automation (PSA) architecture shown in Fig. 4, currently under development. This system is comprised of distributed controllers associated with load-breaking switches. These controllers would allow monitoring of voltages, currents, and other parameters associated with each switch. They could be used in a backup protection mode in addition to being used for implementation of automated restoration algorithms. The PSA system would allow for the interconnected control needed for implementing expert system applications at the substation level.

Finally, a system-wide relaying scheme is also suggested as an expert system implementation. It is well known that the existing protective relaying philosophy has an inherent shortcoming due to its inability to adapt itself to changes in power system operating conditions. This has triggered a number of adaptive relaying approaches which are aimed at making adjustments in the existing schemes so that the schemes may be tuned to the changing operational conditions [54 - 56]. All of the approaches are algorithmic in nature and are not implemented using expert system techniques.

However, another approach for protective relaying has been proposed recently to enable an inherent adaptability [57]. This approach has been further studied in order to analyze an implementation strategy using ICPS [58].

This implementation direction has been proposed for the new EMS architecture where ICPS is used in place of an RTU [59].

A research activity is proposed to study the new system-wide relaying implementation using an expert system approach. The implementation is envisioned as a hierarchical strategy where different expert system decisions are made in a distributed fashion at substations. This protective relaying implementation requires new communication facilities for system-wide data exchange as well as dedicated hardware for high-speed execution of the new relaying function.

4.2. Expert system technology

Research and development in expert system technology is widespread and diverse. Languages, compilers, shells and even operating systems for expert system environments are being actively pursued. Knowledge bases containing 'meta-knowledge' which help steer the efficiency of problem searches and approaches by the inference engines are being actively integrated into expert systems. Tools to distribute or parallelize the expert system functions onto multiple processors are beginning to appear. For that matter, machines which include multiple processors and coprocessors are becoming more common at all levels of computing machinery. The availability and costs of larger and faster memory devices are having great impact on expert system development. Even coprocessors to accelerate expert system operations are seen in many research efforts. Many of these technological advances are essential if expert systems are going to expand effectively into more online and automated real-time processes. To illustrate these concepts, four examples of technological advances for expert systems will be mentioned.

4.2.1. Real-time expert system shells

The shell can be tailored for certain applications. By tailoring an inference engine in an expert system so it expects and handles constantly changing conditions, rather than a fairly static list of facts, the execution performance of an expert system can be greatly enhanced (by a factor of 6) in real-time monitoring applications [60]. The fact that the shell is a C-based shell also accelerates the execution time over similar Lisp-based shells. And finally, the ability of the shell to shuffle

functions out to multiple processors, when they are available, can also enhance the expert system execution times by a factor of 5.

4.2.2. Dedicated architecture

Architectures tuned to the preprocessing requirements and the flow of the data into and out of the expert system can be much more versatile and robust. Multiple processors for general use, or to maintain a specific function, such as communication, memory access, or searching, can be incorporated in an architecture. The microprocessor boom has made this not only possible, but also reasonably economical. This allows architectures to interface numerical processing and expert system processing more effectively. In one such application, processors for data acquisition, processors for signal processing, processors for expert systems, and processors for communications to other systems can be integrated into a single, robust decisionmaking environment [61].

4.2.3. Customized hardware

Customized coprocessors which enhance expert system performance are being studied. Just as floating-point coprocessors, or FFT coprocessors accelerate those functions, coprocessors to accelerate search and matching operations in expert systems have received much attention. For example, much work is being pursued on accelerating the unification function in Prolog, which unifies facts to conditions in a consistent manner [62]. Several coprocessors for accelerating unification have been and continue to be investigated since a Prolog program spends an average of 60% of its time in the unification operation.

4.2.4. Automatic learner

A very important aspect for expanded use of expert systems will be their abilities to comprehend and possibly even expand their knowledge boundaries. Currently, many expert systems have no mechanism to account for the fact that they may be working on the edge of their knowledge domain. More work needs to be done to represent their limits and to allow for automated expansion. This puts one in the domain of a learning machine, and many feel the programs called expert systems do not deserve this title until the systems can learn. The concept of unsupervised and/or supervised learning is being researched extensively, and

has lead to new areas, or old areas being revitalized, such as neural networks. Some work has been done to allow standard expert systems on a microprocessor system to interface to an unsupervised automatic learner [63]. This learner watches the noise on a simulated distribution line and classifies the noise patterns. Unusually distant noise patterns are flagged as events and stored for further examination. This tool can spawn new categories as it sees necessary, although it takes human interaction to give the categories names (such as capacitor bank switches, air switch, arcing fault, etc.).

5. CONCLUSIONS

Analysis of the implementation constraints indicates that expert system applications in power system protection substation control and monitoring are quite difficult. A survey of the existing solutions supports this conclusion since very few applications in this area have been reported so far. The overview of the research activities, undertaken at Texas A&M University with support from industry, indicates possible directions in expert system implementation strategy and hardware/software developments needed to meet the requirements.

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