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IMPLEMENTATION FRAMEWORK OF AN EXPERT SYSTEM FOR FAULT ANALYSIS

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Abstract - This paper is concerned with definition of an implementation framework which would enable classification and comparison of various expert system solutions. The framework description is given by pointing out two most important aspects of the problem. One is the hierarchical nature of the fault analysis process, and the other one is the variety of equipment that may be used for the expert system implementation.

The implementation framework is used to point out various design approaches for the expert system. Special attention is given to the approaches that use both analog signals and contact information as the input data. Examples of new designs of expert systems for fault analysis are discussed.

Keywords: expert system, fault analysis, implementation framework, control and protection equipment.

INTRODUCTION

Application of Expert Systems (ES) to the analysis of power system faults is one of the most frequently investigated problems in the area of ES application to power system monitoring and control [1-3]. The research has resulted in a number of implementation projects that are undertaken around the world [4]. A careful analysis of the implementation approaches indicates different issues that relate to the fault analysis such as alarm handling [5, 6], fault diagnosis [7, 8, 9], fault location [10], disturbance analysis [11, 12], substation monitoring [13, 14], substation switching [15, 16], and restoration switching [17]. All of these issues were investigated separately with very few studies trying to define the overall problem of fault analysis with a clear indication of the possible options for the expert system implementation strategy. This situation has produced a number of different expert system solutions which are very hard to compare due to the lack of a comprehensive implementation framework definition.

This paper is concerned with definition of such an implementation framework which would enable classification and comparison of various expert system solutions. The framework definition is derived by pointing out two most important aspects of the problem. One is the hierarchical nature of the fault analysis decision process, and the other one is the variety of equipment that may be used for the expert system implementation.

The first section of the paper is related to description of the fault analysis problem. Existing equipment that may be used for the expert system implementation is discussed next. The implementation framework characteristics are pointed out in the following section. Some new design approaches for the expert system are proposed at the end.

FAULT ANALYSIS PROBLEM

A careful study of the references indicates that various authors have different interpretations of the fault analysis problem [1-4]. Hence, a variety of expert systems were developed to cope with different aspects of this issue. Definition of an implementation framework requires consistent interpretation of the problem with clear understanding of the decision steps involved.

Fault Analysis Definition

One of the first definitions of this problem had indicated that the main target of the analysis are circuit-breaker and protective-relaying operations [18]. The purpose of the fault analysis, according to the author, is to derive an up-to-date picture of the power-system network and to obtain diagnosis of the trouble. A subsequent reference had pointed out that the whole fault analysis process is performed in order to carry out appropriate restoration switching of the power system [17]. Further study of the problem created new interpretations of the fault analysis as being related to alarm processing [5, 6], fault location [10], disturbance analysis [11, 12], substation equipment diagnosis [13, 14].

The fault analysis problem is actually a combination of the mentioned interpretations. The specific goal of this process is determined by the operator trying to make certain decisions about the state of the system and the needed operations, after a fault event has occurred. Therefore, the fault analysis should be defined as the overall process that guides the operator in making appropriate decisions and actions subsequent to the fault event.

Hierarchical Decision-Making Structure

Based on such a definition, fault analysis process may be considered as a hierarchical decision-making structure with several well defined steps. These steps may be designated as follows:

- data acquisition and preprocessing
- data base updating
- event interpretation
- fault diagnosis
- fault location
- restoration switching

Data acquisition and preprocessing requires a decision about what data is to be collected and what kind of preprocessing is to take place. Typical choices for the input data are circuit breaker and relay contacts as well as samples of analog (voltage and current) signals. The required preprocessing is dependent on the subsequent steps.

Data base updating determines resolution and time window of the fault analysis process. Resolution is related to refreshing time for data base updating. Time window determines time duration of the event that is going to be analyzed. Several decisions have to be made to select appropriate resolution and time window for a given decision step in the fault analysis process.

Event interpretation is essential since it points out what kind of system disturbance has occurred. The main purpose is to identify the fault event and to make a decision to proceed with the analysis. The event interpretation process may be based on different information such as: sequence-of-events, alarms, relay targets, records of transients.

Fault diagnosis is a decision steps that is aimed at identifying consequences of the fault event. It provides information on the faulted sections and related post-fault system configuration. The most common input data used so far for this process are the contact indications obtained from circuit breakers and protection relays.

Fault location decision step points out accurate location of the fault and provides information needed to isolate the fault and to restore the healthy parts of the system. The fault location decision is usually made based on processing of samples of analog signals but circuit breaker contract information may be used as well.

Restoration switching is performed after protective relaying has isolated faulted sections of the system. This action is needed to restore healthy parts of the system that may be non-selectively tripped by the relaying. Restoration switching is also used to restore systems after major black outs. The main decision is related to selection of the system sections to be restored and appropriate switching sequences to be carried out during the restoration. A summary of the fault analysis decision-making hierarchy is shown in Figure 1.

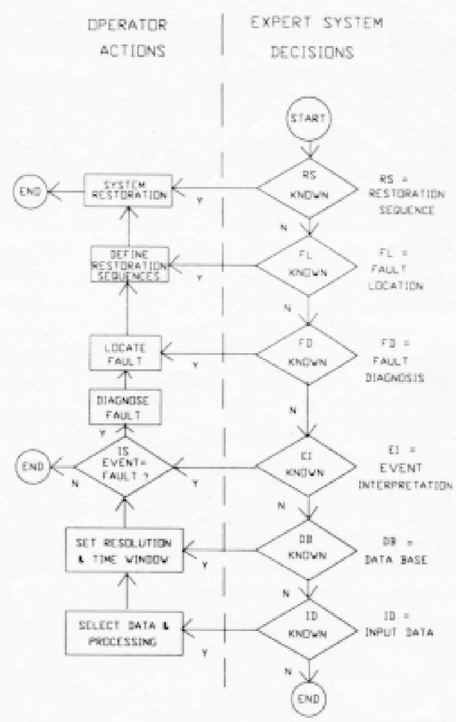

Figure 1. Fault Analysis Hierarchy

FAULT ANALYSIS EQUIPMENT

Implementation of expert systems designed to perform various combinations of the fault analysis decision steps may be carried out using different equipment. This section gives an overview of the equipment designs and their data processing characteristics.

Equipment Designs

A variety of existing equipment may be used for implementation of the fault analysis expert systems. Particular implementation strategy may depend on availability of certain types of devices, which in turn is dependent on specific philosophy that a utility may have regarding the choice of the equipment to be installed. As a summary of the possible equipment designs, Figure 2 gives different devices and their interconnections.

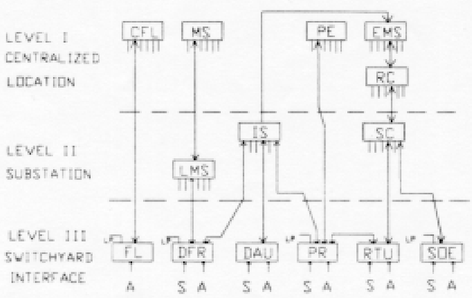

Figure 2. Equipment for Fault Analysis

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

As it may be observed from Figure 2, there are number of possible equipment designs that may be located at different substations throughout the power system. However, all of the existing equipment is used to perform its own designated function, which is usually not implemented using an expert system. On the other hand, that function may be utilized as a part of the fault analysis decision-making process. As a conclusion, implementation of an expert system requires careful integration of the existing equipment and functions with an additional design of the expert system software. This requires further analysis of data processing characteristics of the different equipment.

Data Processing Characteristics

Major differences regarding data processing characteristics are in the following areas: sampling rate, synchronization of input signal sampling, type of input signals, and data base organization.

Equipment shown in Figure 2 has a wide range of options for input signal sampling rates. The highest sampling rates may be implemented in digital fault recorders (several kHz) while remote terminal units of SCADA system may have the lowest sampling rates (couple of hundred Hz).

Synchronization of input signal sampling may be quite different for various designs of the mentioned equipment. Some of the equipment, such as protection relays, have simultaneous sampling synchronization on all input channels. However, not all of the relays are synchronized among themselves. SCADA systems utilize scanning of inputs to the RTUs. Integrated substation control and protection systems may provide sampling synchronization for the entire substation. Most of the equipment provides some sort of time-stamps for synchronization of data samples that are being combined in a centralized data base.

Major difference among the equipment is also related to the type and number of input signals connected from the substation switchyard. The equipment that usually gets most of the system-wide analog and contact data is the SCADA equipment which is connected to the entire power system switchyard through the RTUs. Protection relays get all of the analog signals as well as most of the contact data. Digital fault recorders are connected to selected number of analog and contact signals in a substation. Similar situation is with fault locators which are also connected to selected analog signals. Sequence of events recorders collect most of the contact data in a substation while integrated substation control and protection systems collect almost all analog and contact data available in a substation switchyard.

Data bases differ quite a bit among the equipment. Major difference is in the amount of data collected due to variety of connections to the substation signals. Another difference is in the level of preprocessing that takes place as the original function of the equipment is executed. Finally, a difference exist in the way the collected data is organized in a centralized location.

IMPLENTATION FRAMEWORK UTILIZATION

The hierarchical decision-making structure of the fault analysis process as well as the existing equipment provide a versatile implementation framework that may result in a number of different expert system designs. As indicated earlier, this is illustrated by a large number of reported implementations. However, based on the previous discussion, a more comprehensive analysis of existing designs and future improvements may be performed.

Existing Designs

The most common utilization of the implementation framework for the existing expert system designs is to use equipment which collects contact data coming from protection relays and circuit breakers. Typical equipment used to collect data are RTUs of the SCADA systems, SOE recorders and alarm loggers. It is interesting to note that this implementation approach limits the level of the expert system decision making in the fault analysis process. This may be observed by careful analysis of input signal requirements needed for the decision process outlined in Figure 1. Typical decision steps implemented in this case are the lower steps in the hierarchy providing event interpretation and/or fault diagnosis as the output. The operator still has to rely on other means to make decision about fault location and restoration switching strategy.

This implementation approach introduces some other limitations as well. One typical limitation is processing time required by an expert system to make a decision in a complex case. Usually this time is quite long since data base validity and consistency checks are in this case not easy to perform and this makes the overall decision process quite involved. On the other hand, data base validity and consistency checks are needed since the centralized data base is formed by communicating data from different substations, which may introduce data transmission errors. Yet another problem is associated with a lack of means for a temporal check on the contact data, which again limits capabilities of the decision process.

Future Improvements

Several expert system implementation features were suggested to remedy some of the mentioned problems. A distributed expert system implementation was proposed to improve processing time [19]. An advanced distributed problem solving kernel was developed to enable parallel processing of the expert system tasks in a network of computers.

Yet another approach using decentralized fault diagnosis at the substation level was introduced, which eliminates the need for extensive system-wide communications, and hence the data transmission error impact is reduced [20]. This is made possible by utilizing integrated control and protection systems which are resident in a substation and provide local substation data base. This data base may be used for the local fault diagnosis processing.

Further improvements regarding the means for temporal processing are achieved by using causal and temporal reasoning in implementing expert systems [21, 22].

Finally, it should be pointed out that all of the improvements have not still resolved the major limitation of the mentioned implementation approach. This limitation is related to the difficulty in coming up with the fault location and the restoration switching strategy decisions based only on the available contact data. Some new directions for providing fault location function within the SCADA system are recently introduced, but this development is separate from the expert system implementation [23].

NEW DESIGN APPROACHES

The previous discussion has pointed out major characteristics of the implementation framework utilization for the existing designs. The same general implementation framework consisting of the hierarchical decision-making structure and the variety of different equipment may be utilized in a unique way to enable new design approaches for the expert system. The following discussion gives basic characteristics of some of the new design approaches.

Processing of Fault Signal Recordings

Major goals for the new designs are to make improvements in the areas of the existing designs that are found to have limitations. These improvements could be achieved by including samples of analog signals, together with contact data, in the expert system data base. The information on analog signals may provide temporal check for contact data processing since the sinusoidal waveforms have an inherent representation of time. This feature may be further enhanced by providing synchronized sampling of all voltages and currents as well as circuit breaker contacts at the level of a feeder, substation or the overall power system [24]. Utilization of analog signals may also facilitate validity and consistency check of contact data since the circuit breaker contacts and relay targets are a direct consequence of a given disturbance on the analog signals.

More important aspect of introducing analog signals in the expert system data base is to improve the decision making process for the fault analysis function. Samples of analog signals may be utilized to calculate fault location quite accurately. Furthermore, knowledge on analog signal conditions in the system may facilitate the system restoration procedure as well. By adding these two improvements, the fault analysis decision process may be significantly simplified and made more powerful since the expert system may provide operator with very precise information about the fault and the consequences of the protective relaying operation. Also, a detailed specification of the restoration sequences may be outlined since the fault can be located, the configuration of the system can be verified and the voltage and power flow constraints can be known.

The remaining question is related to selection of equipment to be used for the new expert system implementation. Obviously, there are several candidates from the different types of equipment shown in Figure 2. The trade off between performance and cost has to be carefully investigated to make the best selection. The good candidates are Digital Protection Relays (DPRs), Integrated Substation Control and Protection Systems (ICPSs), and Digital Fault Recorders (DFRs).

An approach undertaken by Texas A&M University (TAMU) was to investigate utilization of DFR equipment for implementation of an expert system for fault analysis. An outline of the equipment configuration is shown in Figure 3. The required input signal processing steps are shown in Figure 4.

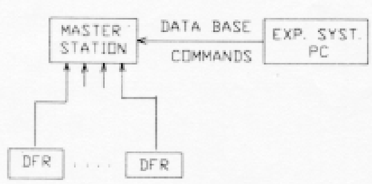

Figure 3. Equipment Configuration

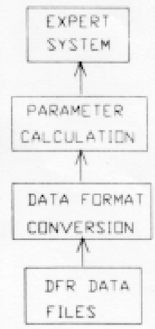

Figure 4. Input Signal Processing Steps

This solution is quite powerful since DFRs provide recordings of both analog and contact signals. Proper design of the signal sampling synchronization and the recorder triggering logic enables collection of time-stamped fault data within substations. Appropriate communication system provides ways to transmit this data to a central location where further preprocessing of the raw signal samples may be carried out. Finally, this new and improved data base is made available for implementation of the expert system logic for fault analysis.

New Expert System Logic For Fault Analysis

Once the improved data base is created at the overall power system level, the question remains as how to implement an expert system logic to utilize this data base.

TAMU investigations have shown that a very powerful logic for fault analysis is the protective relaying logic that is inherently adaptive and selective [25]. This logic is based on both analog and contact signals and may be implemented using digital systems. The main idea is to utilize directional relaying logic with system-wide exchange of data [26, 27]. The most important aspect of this logic is that it determines the faulted section very accurately and within a very short period of time. At the same time it gives an answer about the current system configuration. Therefore, it represent a very efficient logic for fault analysis and is superior in many respects to the previously implemented ones. This logic may easily be implemented using expert system techniques and hence may represent a new design approach for the expert system implementation of the fault analysis function.

A number of different implementation strategies may be utilized to provide system support for this new fault analysis logic. Use of the DFR equipment, as discussed earlier, is one possible approach. Use of a modified SCADA system may be yet another approach. Recent TAMU study indicates that the use of the substation integrated control and protection systems, as substitutes for EMS RTUs, may be the best approach [28]. In this case the system-wide data base and the expert system logic may be implemented in a distributed fashion at substations. The required system-wide exchange of data may be performed through the EMS communication network. This would enable a very fast processing of the logic which in turn would enable either EMS control center or substation operator to respond quickly to the fault disturbances. This new implementation approach is critically dependent on the communication links within the EMS design and further study of this problem is essential when final feasibility of this approach is to be evaluated.

CONCLUSIONS

Discussions given in this paper indicate that:

- The fault analysis implementation framework may be viewed as consisting of the hierarchical decision-making structure and the variety of different equipment designs.
- The expert system designs implemented so far were concentrating only on the use of contact data through SCADA data bases, which has a limiting impact on the fault analysis decision process.
- The new utilizations of the implementation framework enable further improvements in the fault analysis decision process, if analog data is used in conjunction with the contact data.
- The new approach to fault analysis suggested by TAMU introduces system-wide relaying logic and substation ICPS equipment as an improved solution.

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