Intelligent Applications in Substations: Disturbance Analysis

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***Abstract*—This paper is prepared for a Panel Session titled "Intelligent Applications in Substations" and represents a summary of the presentation on the subject of disturbance analysis. The topics covered by this presentation include the use of the following intelligent system techniques: expert systems, neural networks, fuzzy logic, genetic algorithms and advanced signal processing. The applications covered are all related to different aspects of automated analysis of disturbances ranging from classification of faults and power quality disturbances to automated analysis of faults and fault clearing sequences. Each of the mentioned implementations is developed by the author of this paper and his research team, and demonstrated using utility data.**

***Index Terms*—Automation, circuit breakers, expert systems, fault location, fault diagnosis, fuzzy systems, genetic algorithms, neural networks, power quality, wavelet transforms.**

I. Introduction

THIS paper summarizes several implementations that are aimed at analyzing power system disturbances and switching sequences. In each of the applications, a form of an intelligent system technology is utilized. Such techniques are selected to implement automated ways of replicating the thinking and/or actions of utility personal that otherwise do the same tasks manually. The use of intelligent approaches not only provided a way of capturing the expertise, but also enabled development of the solutions that are amenable to future extensions and improvements as additional data and expertise are obtained. The implementation also provides for consistent and timely analysis, the two attributes highly desirable when performing an analysis of critical power system events.

The first application discussed in this presentation is the use of neural networks and fuzzy logic in detecting and classifying the power system faults [1]. While many similar approaches were proposed in the past [2], this implementation is studied to a great detail using utility data and has demonstrated very good performance under practical implementation constrains [3]. The next application is the use of expert systems in analyzing performance of protection relays, relay communication channels and operation of circuit breakers during fault clearing sequences [4]. This idea was introduced by the author in the early nineties [5], and was further tested and deployed as a commercial product in the late nineties [6]. In addition, an approach for determining fault location having only sparse field measurements is also discussed [7]. The proposed technique uses genetic algorithms to match measured and simulated phasors, which leads to a major improvement over any other traditional fault locating approaches [8]. Besides fault analysis, intelligent techniques may be applied to analyze power quality disturbances, which was done by the authors using fuzzy expert system [9]. This enhances ability to make assessment of the causes and consequences of various power quality disturbances [10]. Last, but not least, an expert system combined with wavelet transform application is utilized to improve analysis of circuit breaker operations using signals from the control circuitry [11]. This enables not only a quick analysis of recording obtained during maintenance tasks but also a "continuous" analysis of the breaker performance during any in-service switching actions, which is a major improvement over traditional maintenance approaches [12].

In all of the mentioned implementations the major design goal was to capture the expertise of utility staff and apply it to perform the analysis in an automated way. The presentation points out the benefits of using intelligent techniques for this purpose.

II. Intelligent Substation Applications

Each of the applications assumes that certain field data collected by substation IEDs is used for performing the analysis. Some applications require additional power system model or substation configuration data. The algorithms used for performing the analysis are implemented at either the substation PC or at a central location. The following is a description of each application and related implementation.

A. Fault Detection and Classification Using Neural Networks and Fuzzy Logic

This application introduces several enhancements of the mentioned original version of the algorithm [1]. They include: a.) Improved preprocessing of neural network inputs affecting the algorithm sensitivity; b.) Redefined concept of supervised learning which now allows improved neural network generalization capabilities; c.) Attuned fuzzy decision rule

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allowing an interpolation of neural network outputs; d.) Results of extensive solution evaluation, which cover a variety of power system operating conditions and events. The new version of the ART neural network algorithm is compared to the original version using elaborate modeling and simulation set up that represents a segment of an actual 345kV network from CenterPoint Energy in Houston.

The use of neural nets has enabled the fault detection and classification tasks to be performed without the need to have traditional settings. This approach allows for more secure and dependable decision-making of the relaying function since the errors due to possible inappropriate selection of the settings are eliminated. This is particularly important when the relaying decision has to be reached during dynamically changing power system conditions, which may deviate from the anticipated events. An example of such a situation is a cascading event that causes the power system topology to dynamically change causing the traditional relays to operate due to inadequate settings. The use of neural nets aloes correct decisions to be made even under such dynamically changing conditions.

While the potential benefits of using neural nets for the relaying function are appealing, one needs to recognize that the use of neural nets requires rather elaborate process of training the net for various power system conditions. This translates into the need to develop detailed models of the power system that can be used to simulate a number of fault scenarios that can be used for neural network training.

This presentation also indicated how the Fuzzy logic approach could be utilized to improve the performance of the neural network solution for the cases when the measured data is incomplete or imprecise [3].

B. Analysis of Fault Clearing Sequences Using Expert Systems

The traditional DFR systems consist of recorders distributed in substations and a master station located in a centralized office. A variety of communication procedures and protocols may be implemented for bringing the data from the recorders to the master station. Depending on the specific utility needs and requirements, the number of recorders per a substation/region may vary, and there may be multiple master station locations. Once the data is brought to the master station, it may be archived in a repository and viewed by the engineers involved in the analysis using custom software supplied by the vendor of the given DFR system at a later time.

Due to evolving needs and requirements, a given utility may acquire a variety of DFR system solutions and/or upgrades over a period of time. Typical situation is that a utility may end up having several DFR systems (recorders and matching master stations) supplied by different vendors, or several generations of the DFR hardware and/or software supplied by the same vendor over the years. In most cases, the end result of the evolution is that installed systems do not allow an easy data integration and information exchange, which makes the use of the systems rather difficult.

The examples of the limitations in the area of data integration are: the lack of a common data base solution for storing the records coming from different types of DFRs and/or recording systems, inability to view all the records collected by different type of recorders and/or recording systems using the same viewing software, the need to have a number of data file converters to accommodate legacy data records that may not be available in the COMTRADE standard format, difficulty of interfacing different types of recorders and/or master stations using standard LAN protocols. The examples of the limited information exchange are: unavailability of automatic means for extracting the information required by different utility groups (protection, maintenance, system operators), the lack of convenient means for retrieving only the essential information from sometimes an overwhelming amount of recorded data, inability to disseminate the information over a LAN using standard LAN/Web services.

The resulting implementation requirements are outlined in this presentation and then the implementation options are described [13].

The use of expert system has allowed the expertise of the utility engineers to be captured in a formal solution that can be then used across the power system for a consistent and automated process of the analysis. Several advantages of this solution are recognized, such as speed of operation and ability to analyze rather complex cases with a very simple software solution. Another important feature of this solution is the ability to expand the expert system rules to include new cases of the analysis or an improved analysis. The ability to produce the results of the analysis very fast has brought the use of such results in the real-time realm of control opportunities, which was not available before.

C. Fault Location Using Genetic Algorithms

The fault location in the transmission network is an important issue since identifying an accurate fault location can facilitate repairing the damage and restoring the transmission line rapidly. If a fault location cannot be identified quickly, and this makes the transmission line outage time prolonged during a period of peak load, severe economic losses may occur and reliability of service may be questioned.

A lot of efforts have been spent on the topic and several solutions were proposed in the literature. These applications have a common requirement: the measurement must be obtained from one or both ends of a faulted line. For some systems, such as the CenterPoint Energy transmission system, only sparse recorded data at limited substation locations are available. When a fault occurs in such systems, only a few (two or three) recording devices are triggered. The most likely case is that the measurements could not be obtained at either or both ends of the faulted transmission line. Under this situation, the mentioned methods could not be applied correctly.

The method proposed in this presentation aims at this situation and tries to give a proper solution even when only the sparse measurements are available [7].

The method benefits from two new approaches: extended use of the power system model and the use of a powerful global optimization technique using genetic algorithms. The combination of the two approaches produced a new opportunity for locating faults in the cases where no other automated means for the same situation are available. The existing approaches that are manual are far from being optimal, and may take considerable time and expertise to implement. The new approach can made fully automated, and once implemented, does not require any further expertise on the part of the user.

D. Analysis of Power Quality Disturbances Using Fuzzy Expert System

In a power system, faults, dynamic operations, or non-linear loads often cause various types of power quality disturbances such as voltage sags, voltage swells, switching transients, impulses, notches, flickers, harmonics, etc. On the other hand, the increased use of sensitive electronic circuitry by industrial and residential customer, as well as the progress of utility deregulation and competition has imposed greater demand on the quality of power. Consequently, the study aimed at detecting and analyzing as well as eliminating or minimizing the effects of power quality disturbances on industrial and customer loads has assumed greater importance.

One critical aspect of power quality studies is the ability to perform automatic power quality monitoring and data analysis. Usually, utilities install power quality meters or digital fault recorders at certain locations so that various power quality events can be recorded and stored in the form of sampled data for further analysis.

Efficient and prompt detection, classification, and characterization of the events as well as further identification of the location of these events facilitate maintenance and control of the system, and improve system stability and reliability. Another principal aspect of a power quality study is coordination between the power system behavior and equipment performance. It is desired that the response of the sensitive equipment during the event be explained and correlated to specific features of the event, so that either the system behavior or the equipment operating characteristics can be tuned for improved ride-through ability or immunity of the equipment to specific events.

It has been noted that the activities of detecting and classifying of power quality events, characterizing and locating events, studying equipment sensitivity, and modeling of the system and equipment are closely related and interdependent. Hence it is natural and desirable that the data processing and analysis as well as modeling and simulation of the system and equipment be studied in one unified framework. This presentation introduces a new software implementation concept for such integration [10].

The use of expert system and Fuzzy logic has enabled the entire process of detecting, classifying and characterizing the power quality events to be fully automated. This provides the required convenience of being able to track large number of such disturbances without an excessive use of the operator's time. With such a solution, a number of permanent power quality monitoring stations can be installed at various critical locations and the monitoring and analysis can be fully automated.

E. Analysis of Circuit Breaker Performance Using Wavelet Transform and an Expert System

Circuit breakers represent one of the most critical power apparatus in the power system. They are used to change topology of the power system to accommodate various configurations in routing the load. The breakers are also used to isolate faulted parts of the system as a part of the protective relaying operation. Due to such a critical role, the breakers need to be ready to operate at all times and any disruption in their operation may have costly consequences. However, preventive maintenance and testing intervals can be many years apart. To prevent circuit breaker miss operation, the breakers are inspected and monitored on regular basis. In performing such a task, one obstacle is quite obvious: an average size utility may have thousands of breakers in service. The sheer number of breakers makes it almost impossible to perform the inspection and monitoring with sufficient frequency. The maintenance cycle may be as long as a year, which leaves room for number of early signs of deteriorating performance to go undetected.

Typical existing circuit breaker inspection practice is to use portable recording sets that are carried from substation to substation and connected to the breaker manually by the maintenance staff [12]. Once the recording set is connected, the circuit breaker is forced into operation and the recordings of signals from the control circuitry are taken. The maintenance crew visually analyzes the recordings on the spot and, based on the abnormalities that appear in the waveforms, the breaker corrective maintenance is initiated. This process is rather tedious and subject to an interpretation and particular expertise of the individuals involved. As a result, the post-inspection actions may vary from a crew to a crew and the inconsistent breaker corrective maintenance may result in different levels of readiness of the circuit breakers even after the inspection is performed.

The two mentioned problems, namely the large number of breakers causing the long intervals between inspections and the diagnosis inconsistency causing uneven maintenance practices, led the utilities to consider more efficient and consistent means of monitoring and analyzing breaker operations. This presentation describes a solution that is based on the use of advanced signal processing and expert system concepts [11]. The implementation is aimed performing automated analysis of circuit breaker conditions. The system collects samples of signals obtained from a circuit breaker control circuitry, extracts the required signal features and passes them through an expert system for reaching the final conclusions. Since the whole process is automated, the time required to perform the diagnosis and maintenance may be significantly reduced. At the same time, since the rules for the analysis are hard coded, the diagnosis is very consistent. To facilitate the storage and retrieval of both the raw data and results, web-based database access techniques are also implemented. The main features of a system developed for CenterPoint Energy in Houston are described.

The use of advanced signal processing and expert system software allowed for full automation of the analysis process providing an opportunity for a "continuous" monitoring of the CB operating performance. If a data acquisition unit that allows for permanent recording of the control circuit waveforms is installed, the developed software could analyze the breaker operation each time CB performs a switching action, either caused by a relay action, or by an operator. This opportunity changes the whole concept of the maintenance and monitoring since the time interval for such an action is now reduced to the instant of CB operation. In contract with such an analysis being performed once a year, this represents a major move towards "just-in-time" maintenance concept.

III. Conclusions

Several major benefits of the use of intelligent techniques are experienced in the following areas:

- Expertise of utility staff is extracted during the process of designing expert system solutions, and this was very helpful in preserving this expertise in the case the experts are not readily available in the future.
- During design of neural network applications, a large number of fault studies using simulation was pursued, which gave a chance for development of detailed models of the power systems at hand that can be used for various other studies in the future.
- Fuzzy logic applications required some empirical knowledge to be acquired during study of various power quality and fault events, which gave additional insight in the phenomena.
- Use of wavelets enabled some unique understanding of the signal properties of interests that were not possible with any other techniques used previously, which enhanced the overall signal analysis capability.
- Performing optimization using genetic algorithms illustrated how shortcoming of some traditional optimization techniques can be overcome in the case when a global optimum is needed.
- Automation of the analysis procedures saves time, and this was a critical requirement in many of the mentioned applications.

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VI. Biography

Mladen Kezunovic (S'77, M'80, SM'85, F'99) received his Dipl. Ing. degree from the University of Sarajevo, the M.S. and Ph.D. degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively. He was with Texas A&M University since 1987 where he is now the Eugene E. Webb Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for equipment evaluation and testing as well as application of intelligent methods to control, protection and power quality monitoring. Dr. Kezunovic is a registered professional engineer in Texas, member of CIGRE, and a Fellow of the IEEE.