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AUTOMATED FAULT ANALYSIS USING INTELLIGENT TECHNIQUES AND SYNCHRONIZED SAMPLING

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Summary: This paper describes a new concept of automated fault analysis where fault transients and changes in power system equipment contacts are processed on-line. This allows faster confirmation of correct equipment operation and detection of unexpected equipment operations, as well as increased accuracy of fault location and analysis. In addition, the paper gives three independent utility examples that required automating some aspect of the fault analysis process. One approach is the substation level analysis, where local digital fault recorder (DFR) data is processed at the substation to obtain accurate fault location and analysis. Another approach is DFR data analysis at the master station location, where all DFR data files from remote locations are concentrated and processed. Finally, an example of a highly accurate fault location system for series compensated lines using global positioning system (GPS) synchronization is presented. This paper presents summary of the main accomplishments for each of the projects.

Keywords: Automated Fault Analysis - Synchronized Sampling - Digital Fault Recorders - Signal Processing - Fault Location - Protective Relays - Expert Systems

INTRODUCTION

Development of new technologies such as intelligent systems and synchronized sampling as well as increased utility deregulation and competition are leading to the introduction of new applications and solutions in the fault analysis area.

The early approaches to fault analysis using intelligent techniques were related to alarm processing in a Supervisory Control and Data Acquisition (SCADA) system [1]. At that time, expert system techniques were utilized to implement an automated analysis of alarms

[2]. The SCADA based solutions did not have the capability to calculate fault location, and processing of analog waveforms was not done due to the lack of sampled waveform data. Further improvements of the overall solution were achieved using neural network (NN) implementations [3, 4].

A study of the possible approaches to fault analysis using digital fault recorder (DFR) data revealed some advantages due to the ability to calculate fault location and correlate waveform samples with protective relay and circuit breaker contact operation. This has enabled a new approach to fault analysis to be implemented using expert systems and DFR data [5, 6, 7]. Further developments in this area indicated that a very accurate fault location approach can also be developed using DFRs enhanced with accurate data acquisition interfaced to global positioning system (GPS) receivers [8, 9]. Use of neural nets for fault detection and classification was also investigated to enhance the overall fault analysis solution [10, 11].

The general concept of automated fault analysis using substation data, expert systems and synchronized sampling is presented first in this paper. The new concept is related to analysis of the data coming from variety of substation equipment such as DFRs, sequence of event recorders (SERs), protective relays, and other intelligent electronic devices (IEDs)

This paper also summarizes results from three different projects aimed at automated fault analysis. Two projects demonstrate possible approaches to automated fault analysis using DFR data and expert systems. The third project illustrates a highly accurate fault locator based on synchronized sampling using commercial data acquisition system with GPS receivers. A set of conclusions and related references are given at the end.

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A NOVEL APPROACH TO AUTOMATED FAULT ANALYSIS

The ultimate fault analysis system should provide results of a detailed system-wide analysis of an event to the system dispatchers and protection engineers within seconds after the event occurred. This may not be feasible with the existing SCADA technology. The main reason is the lack of detailed information about transient waveforms and contact changes that are not readily available through Remote Terminal Units (RTUs) of a SCADA system. On the other hand, such information is available through other Intelligent Electronic Devices (IEDs) including DFRs, Sequence of Event Recorders (SERs) and Digital Relays (DRs). A new concept for fast and accurate fault analysis can be developed using this equipment technology, high-speed data communication infrastructure and advanced software techniques.

Various types of users have different needs regarding the time response and/or extent of information provided by the fault analysis system. The system dispatchers are interested in getting the condensed fault analysis information as soon as possible after the valid fault occurs. Their main interest is determination of accurate fault location and switching equipment status that enables them to make decisions about the system restoration. The protection engineer, on the other hand, is more interested in getting detailed and specific information regarding the operation of the protection system and related equipment during the event. The time factor is not as strict as for the system dispatcher.

In this section we present the concept of an integrated fault analysis system that can be built with existing technology and can satisfy both types of users. The subsequent sections give brief presentations of various research and development projects that are an illustration of possible steps towards the final system solution for automated fault analysis.

Figure 1 presents the block diagram of one possible implementation of an integrated system. Each substation is equipped with a PC (low end Pentium machine) that collects data from different devices (e.g., DFR, SER, DR), and analyzes that data locally. The results as well as raw data files are communicated to the central file server in a common COMTRADE format [12]. The substation analysis provides fault location and fault type based on the data recorded at this location. This data can be made available to the system dispatcher and protection engineer within a minute after the recording was made by appropriate device. The information is communicated in the form of a fax.

After this initial faxing, the substation PC establishes communication with the Central File Server and uploads event data to it. The System Wide Analysis software monitors incoming event files and correlates files coming from different locations based on their accurate time stamps and samples that are synchronously taken at all substations using GPS receivers for synchronization. The system fault analysis is then executed using data from various locations to produce a summary report for protection engineers.
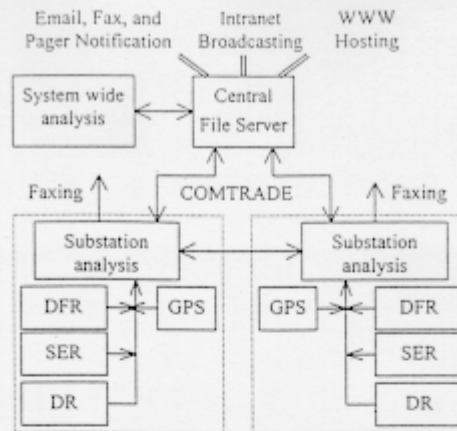

Figure 1. Conceptual diagram for the new fault analysis approach

It is important to note that such an integrated solution is not yet available since the design provisions to implement the synchronized sampling for all substation data acquisition systems are not readily available [13]. In addition, utilities are still researching various options to provide standard communication architecture allowing high-speed substation-wide data acquisition and transfer to the centralized substation and system level location [14].

An assessment of the existing technology reveals that future developments in the IEDs for substation metering, control and protection are leading to the following expected improvements [13]:

- Increased accuracy of the A/D subsystem
- Synchronized sampling on all input channels
- Multiple communication interfaces for high-speed data transfer
- Availability of extensive signal processing for calculation of various measuring quantities

Combined with on-going developments in the utility communication architecture, it is expected that the substation IEDs will provide an impressive level of detail of the data needed to perform automated fault analysis.

In the meantime, some solutions that are less involved can be implemented using the technology that is readily available. In particular, DFR data analysis can be automated using expert system technology. In addition, fault location accuracy can be improved using GPS receivers to synchronize customized data acquisition units located at two ends of a transmission line. The remaining sections of this paper illustrate how several different approaches can be undertaken using the existing technology. It is expected that in the future, the substation equipment will have all the required design provisions so that an optimized use of the technology can be achieved maximizing the cost/performance benefit.

PROJECT I: AUTOMATED HIGH-SPEED FAULT ANALYSIS AT THE SUBSTATION LEVEL

Occurrence of a fault on a major transmission line may endanger the operation of a bulk power system and potentially lead to costly outages. If the fault analysis results are not available to system operators shortly after the fault occurred they might not be able to reach an optimal decision regarding the restoration of a line. In the era of increased competition between utilities due to the open access and retail wheeling, any unnecessary delay of energy supply restoration compromises a utility's competitive position.

The project described in this section is aimed at utilizing existing DFR data to provide a system dispatcher with accurate and timely information regarding the fault type and fault location, as well as an analysis of the operation of protection system and related equipment. The dispatcher can use this information to decide if a transmission line should be restored back to service or a maintenance crew dispatched.

The block diagram of the system that was developed is shown in Figure 2. The expert system communicates with DFR over a high-speed parallel link. It interrogates the DFR for new recordings on a continual basis. A new data file is copied from a recorder and immediately analyzed. The analysis report is created and faxed to the system dispatcher and to the protection engineer's office. The whole process takes less than a minute, so valuable information is available to the system dispatcher in a relatively short period of time after a fault was recorded by the DFR.

The analysis report typically contains the following information:

- Event date/time stamp and DFR identification
- Fault type, fault location, and transmission line involved
- Relay tripping times, breaker opening times, and carrier signaling
- Snapshot of RMS values for selected analog channels

The fault analysis logic incorporated in the expert system's knowledge base relies on signal processing algorithms to extract aggregate parameters such as RMS values for phase currents and bus voltages from samples recorded by DFR. These parameters are then passed through the set of rules that represent relationships between system variables during different fault (or normal) operating conditions. The mathematical relationships between various parameters for certain fault types are shown in Table I. [5].

Figure 2. Diagram of the substation analysis system

This set of rules represents the application's knowledge about the operation of a power system section in the form of "rules of thumb". The rule base is expandable and can be changed over time, when a better understanding of particular operations of power system equipment becomes available.

To facilitate modularity and extensibility of the analysis logic, a "C Language Integrated Production System" (CLIPS) expert system tool was embedded in the application. This tool allows addition of new rules which specify a new set of actions to be performed for a given power system operating condition.

Figure 3 shows an example of a CLIPS rule to determine if particular conditions for a phase-to-ground fault are met. The exact thresholds (multiplication coefficients) will change from substation to substation, and may need to be determined by trial and error as well as modeling and simulation.

The expert system software is fully automated. Once configured, no operator interaction with the system is needed. The system reports its operating status on a daily basis by sending a fax message to the dispatcher's and protection engineer's office.

```
(defrule  AG_fault
  (ipre ?iap ?ibp ?icp ?i0p)        (iflt ?ia ?ib ?ic ?i0 )
  (vpre ?vap ?vbp ?vcp ?v0p)        (vflt ?va ?vb ?vc ?v0)
  (vlp ?vabp ?vbcp ?vcap)           (vl ?vab& ?vbc ?vca)
  (test (> ?i0 (* 0.20 ?ia )))      (test (> ?ia (* 1.40 ?iap)))
  (test (< ?ib (* 0.33 ?ia )))      (test (< ?ic (* 0.33 ?ia )))
  (test (> ?v0 (* 8.00 ?v0p)))      (test (< ?va (* 0.90 ?vap)))
  (test (> ?vb (* .96 ?vbp)))       (test (> ?vc (* 0.96 ?vcp)))
  (test (< (abs (- ?vb ?vc)) (* .05 ?vbp)))
  (test (< (abs (- ?vab ?vca)) (* .2 ?vabp)))
  (test (< (abs (- ?vbc ?vbcp)) (* .2 ?vbcp)))
=>
  (format t "AG_Fault fired%n")
  (assert (FaultType "Phase A to ground fault")) )
```

Figure 3. Example of a CLIPS rule

Table I. Behavioral Patterns of the Basic Parameters

Event Type	0 Sequence Current	Faulted Current	Unfaulted Current	0 Sequence Voltage	Faulted Voltage	Unfaulted Voltage	Line Voltage
a - g	$I_0 > .2I_a$	$I_a > 1.4I_p$	$I_{b,c} < .33I_a$	$V_0 > .04V_n$	$V_a < .9V_n$	$V_{b,c} > .96V_n$	$V_{ab} \approx V_{ca}$
a - b	$I_0 < .01I_a$	$I_a > 1.4I_p$ $I_b > 10I_p$	$I_c < .1I_a$	$V_0 < .01V_n$	$V_a < .8V_n$ $V_b < .7V_n$	$V_c > .99V_a$	$V_{ca} < .8V_{ref}$
a - b - g	$I_0 > .1I_a$	$I_a > 1.4I_p$ $I_b > 10I_p$	$I_c < .1I_a$	$V_0 > .05V_n$	$V_a < .8V_n$ $V_b < .8V_n$	$V_c > .98V_a$	$V_{ca} < .8V_{ref}$
a - b - c	$I_0 < .03I_b$	$I_f > 10I_p$		$V_0 < .01V_n$	$V_f < .8V_n$		$V_{lf} < .8V_n$
a-b-c-g	$I_0 < .03I_b$	$I_f > 10I_p$		$V_0 < .01V_n$	$V_f < .8V_n$		$V_{lf} < .8V_n$

PROJECT II: AUTOMATED SYSTEM-WIDE FAULT ANALYSIS

The objective of this on-going research project is to streamline DFR data files that are coming from many different locations and archive them on a corporate LAN using certain classification criteria. The basic data flow diagram is shown in Figure 4. The DFR Master Station PC's #1 through #3 are responsible for communicating with remote recording units via dial-up modem lines. The Master Station units can be configured to automatically poll remote recorders on periodic basis and retrieve new events, or substation DFRs can be set-up to automatically call a Master Station when they have a new event to report. For this project, the second option was used.

It is worth mentioning, at this point, that this system is configured to classify files coming from DFRs made by two different vendors. The classification system has been generalized to allow easy incorporation of additional vendor's digital recording systems, as long as the particular DFR vendor provides DFR file format description. For utilities that may have DFRs from multiple vendors, this classification system feature provides a common platform for fault analysis and the distribution of results. In addition, the common platform eliminates the need to train employees to use multiple DFR manufacturer analysis packages.

To facilitate the classification process as well as distribute classification results across the corporate Intranet, a dedicated File Server PC and a Classification engine PC are secured. The Classification Engine is the "brain" of the system. It monitors assigned incoming file directories on a File Server and detects any new DFR data file that has been copied from Master Stations. These new files are processed using built-in logic to produce a classification report. Finally, the Classification Engine automatically converts the raw DFR data file into the COMTRADE format [12] and copies it with the associated classification report to an assigned directory on Windows NT File Server.
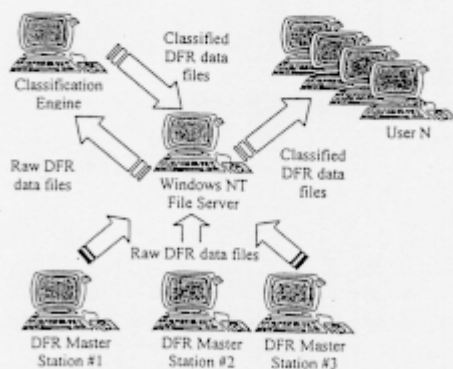

Figure 4. Classification system block diagram

The File Server is a repository of both the raw DFR data files in its native format and the processed DFR files in the COMTRADE format. The easy access to the processed DFR files is facilitated by archiving all data files into three categories (high, medium, and low priority) based on certain criteria. A separate software package for viewing the processed DFR files is provided. This package provides an integrated environment for displaying both the conclusions about the analysis of a selected DFR file, as well as graphics in the form of analog and digital traces.

One of the tasks of the Classification Engine is to reduce the time that system protection personnel spend on manual examination and archival of DFR records. This system automatically classifies and filters DFR records based on the following broad criteria:

- The fault condition exists and clearing time is satisfactory.
- The fault condition exists and clearing time is longer than expected.
- The fault condition exists and breaker restrike and/or ferro-resonance occurs during fault clearing.

Table II shows the list of signals that are used for the DFR file classification logic. If the signal is not monitored in a particular DFR configuration, associated classification logic can not be implemented. In the case where only the two phase currents plus residual current are monitored, the third phase current will be calculated automatically by the Classification Engine.

The following parameters are extracted and/or calculated from every DFR record:

- Relay trip times and relay pick-up time
- Breaker open/close times and breaker pick-up time
- Breaker failure start times
- Carrier start/receive times
- Calculated fault inception time

The classification logic is based on the analysis of the above parameters. The following are the events that can be recognized and flagged by the system:

- Slow relay clearing
- Breaker failure or slow breaker clearing
- Breaker restrike
- Carrier misoperation
- PT Ferro-resonance
- Reclosure failure, Line lockout

Table II. Input signals used by Classification Engine

Digital	Primary and backup relay trip Breaker open position Breaker close position Breaker failure (BF) contact Carrier Start and Carrier Received contacts	
Analog	At least two phase currents Residual current All three phase (bus side) voltages Residual (neutral) voltage	(Ia, Ib, Ic) (Ir) (Va, Vb, Vc) (Vr)

PROJECT III: GPS BASED HIGH ACCURACY FAULT LOCATION

As noted earlier, the accurate and timely information regarding fault location, after a transmission line fault has occurred, is most important to system dispatchers. They need to confirm and isolate the faulted section before any system restoration is attempted. Then dispatch maintenance crews directly to the fault site.

Most of the existing fault location algorithms use data from one line end, due to the large cost of additional equipment involved in obtaining the data from the other end as well [15, 16]. Recently, the cost of the necessary hardware is rapidly decreasing, which makes implementation of two ended fault location algorithms cost effective for critical transmission lines. The two ended fault location algorithms are inherently more accurate and robust than single ended ones [8, 17].

The fault analysis system presented in Figure 1 incorporates design features needed for implementation of an advanced fault location technique based on synchronized sampling. Figure 1 shows the case where two neighboring substations are equipped with GPS receivers. The GPS receivers are used for accurate synchronization of recording devices. Two substation PCs communicate with each other via dial-up modem lines and exchange fault waveform samples taken synchronously.

One of the most important requirements for this fault location algorithm is a fast, reliable and accurate data acquisition subsystem. This can be achieved either by using separate data acquisition with customized signal conditioning hardware, or making improvements in the existing data acquisition subsystem built in the customized DFR [18]. The first approach increases the cost and complexity of the hardware installed in the substation. The second is preferred if the existing DFRs can be upgraded.

As total cost of implementing this advanced fault location system decreases over time, we expect wider acceptance of the technology by utilities that want to gain comparative advantage by having accurate and up-to-date information regarding their transmission grid.

High sampling rate requirements are imposed on the data acquisition system due to the fact that the fault location method is based on discretization of Bergeron's traveling wave equations or lumped parameter line equations [19, 20]. In order to derive these equations we can consider the unfaulted long transmission line shown in Figure 5. A transmission line longer than 150 miles can be represented as an L-C circuit, since the contribution of the resistance and conductance to the series impedance and shunt admittance can be neglected. The length of the line is d. The l and c are the series inductance and shunt capacitance per unit length. The voltage and current at the point F, at distance x from the sending end S is given by

$$v_F(t) = \frac{z}{2}\left[i_S(t - \tau_x) - i_S(t + \tau_x)\right] + \frac{1}{2}\left[v_S(t - \tau_x) - v_S(t + \tau_x)\right] \quad (1)$$

$$i_F(t) = -\frac{1}{2}\left[i_S(t - \tau_x) + i_S(t + \tau_x)\right] - \frac{1}{2z}\left[v_S(t - \tau_x) - v_S(t + \tau_x)\right] \quad (2)$$

These equations follow directly from Bergeron's traveling wave equations. Here, z is the characteristic impedance of the line and τ_x is the travel time to point F from S. They are defined as

$$z = \sqrt{\frac{l}{c}} \quad , \quad \tau_x = x\sqrt{lc} \quad (3)$$

The voltage and current can also be written in terms of the receiving end R voltages and currents by replacing the subscript S with R and changing the travel time τ_x to τ_{d-x}, which is the time to travel from end R to F. Now, if a fault occurs at F, then the voltage at point F due to the end S voltages and currents will be the same as the voltage at F due to the end R voltages and currents. Thus the fault location equation becomes

$$\frac{z}{2}\left[i_S(t - \tau_x) - i_S(t + \tau_x)\right.$$
$$\left. - i_R(t - \tau_{d-x}) + i_R(t + \tau_{d-x})\right]$$
$$+ \frac{1}{2}\left[v_S(t - \tau_x) + v_S(t + \tau_x)\right.$$
$$\left. - v_R(t - \tau_{d-x}) - v_R(t + \tau_{d-x})\right] = 0 \quad (4)$$

The distance to the fault does not appear explicitly in the equation. When the equation is discretized based on the sampling interval, the travel times to the point F from either end will not be exact any more. The right hand side of Equation 4 will have a finite non-zero value. Now, based on the sampling time step, the line can be divided into a number of discrete points, and Equation 4 can be used to compute the error voltage at each of those discrete points. The point that yields the minimum error value is the estimate of fault point.

This method is strongly dependent on the sampling frequency. To reduce this requirement, the approximate point is used as a guideline. Once the minimum error point is obtained, the voltages and currents at the points adjacent to this point can be computed using the discretized versions of equations 1 and 2, the single end equations.

The line section between the adjacent points is now modeled as a short transmission line and the fault location is calculated more accurately. Further accuracy improvements can also be achieved for mutually coupled lines if the synchronized measurements are available from the terminals of the coupled lines [21].
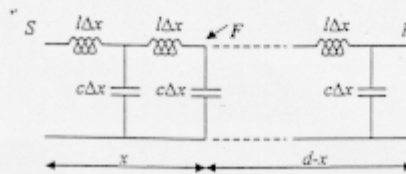

Figure 5. Unfaulted long transmission line

CONCLUSIONS

This paper has introduced a general concept of automated fault analysis utilizing data collected by various substation data acquisition equipment, and synchronized using GPS receivers. Since the technology for a full-blown solution is not yet readily available, a variety of solutions can be implemented using existing advanced technology. The following are the projects and related benefits that are being implemented by Texas A&M University and its utility partners:

- High-speed automated substation based fault analysis using DFR data.
- Integrated system wide automated analysis of DFR data from different DFR systems.
- Accurate fault location utilizing synchronized samples from two ends of a transmission line using GPS receivers.

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