USE OF INTELLIGENT SYSTEMS AND ADVANCED SIGNAL PROCESSING TECHNIQUES IN AUTOMATED ANALYSIS OF DISTURBANCES AND PROTECTIVE RELAY OPERATIONS

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ABSTRACT

This paper describes recent implementations and proposes new developments related to automated fault and disturbance analysis. An advanced expert system for automated analysis of faults and related operations of protective relays using DFR data is described first. Further improvements in the fault location using synchronized sampling are discussed next. Possibility for DFR modifications to allow for continuous recording of power quality disturbances and implementation of an automated system for analysis of those disturbances is also proposed.

keywords: fault analysis, fault location, digital fault recorders, power quality, protective relays, disturbance monitoring

INTRODUCTION

The restructuring of the power industry has introduced even more stringent criteria for supervising the system operation and monitoring performance of the equipment. Translated into the field of monitoring of operation of protective relaying and related equipment and analyzing system disturbances, the new criterion means better, faster, and more reliable automated systems [1,2].

A very common approach for the monitoring and analysis of fault disturbances and related equipment operations is to use digital fault recorders (DFRs). These instruments are very useful since they acquire both analog (waveforms) and digital (contacts) information. The data is sampled synchronously in a given substation and allows detailed visual analysis of the events and equipment operations. The data can be transferred to a Master Station located at a central office where system data may be displayed and further analyzed by the operators.

This paper introduces a concept of an advanced system for automated fault analysis, accurate fault location, and extensive power quality monitoring based on the DFR infrastructure. The existing DFRs can be modified to provide the required data acquisition features. The existing communication network and processing power can be extended to accommodate the required data acquisition, processing and analysis. New software can be developed to accomplish the automated analysis.

The first part of the paper describes an automated system for fault analysis developed using expert system technology. The system is capable of analyzing the DFR data either locally in a substation or a central location. A variety of communication services are also implemented to facilitate storing, viewing and distributing of the analysis reports.

The second part of the paper discusses possibilities for accurate fault location using synchronized sampling. An algorithm that uses data synchronously taken at both ends of a line is introduced. The required modifications of the DFRs to provide GPS controlled sampling of the input data are proposed.

The last part of the paper points out how the automated fault analysis and synchronized sampling technologies can be extended to the monitoring of the power quality disturbances. Further modifications of the DFR are proposed to allow for continuous monitoring of the events. A variety of digital signal processing algorithms for power quality monitoring and analysis are referenced.

The conclusions summarizing the main points of the paper are given at the end.

NEXT GENERATION SYSTEMS FOR AUTOMATED DFR FILE CLASSIFICATION

Various types of users have different needs regarding the response time and/or extent of information provided by the fault analysis system (see Figure 1). The protection engineer is interested in getting detailed and specific information regarding the operation of the protection system and related equipment during the event. The technicians require a summary of the fault classification to help them troubleshoot incorrect operations of protection equipment. The system dispatchers are interested in getting the condensed fault analysis information as soon as possible after the occurrence of a fault. The system dispatcher's main interest is determination of accurate fault location and switching equipment status that enables them to make decisions about the system restoration.

In this paper we present the concept of an integrated fault analysis system that can be built with existing technology and can satisfy all three groups of users – protection engineers, dispatchers, and technicians. [3, 4]

The generic framework for such a system that is applicable to any existing DFR model and conforms to the variety of recording practices within utility companies is depicted in Figure 2.

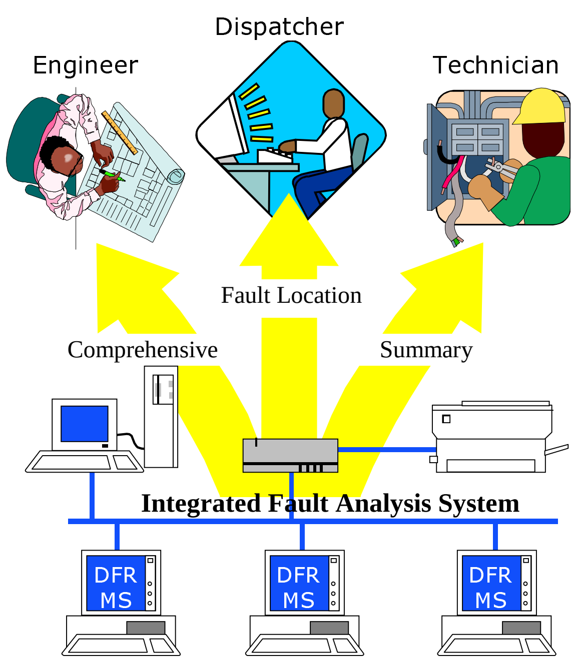

FIGURE 1: Major user groups and levels of information requested by each group

The system is based on client/server architecture. The server side consists of an Expert System PC and associated Event Database, and a number of remote PCs located in the substations or switchyards. These PCs communicate with DFRs via parallel or serial communication link, process event files locally, perform file compression and finally upload results to Expert System for further processing and archiving. This ensures that the time from event recording until the analysis is available at central location is short and system's response is suitable for use by dispatcher. Optionally, dedicated Master Station PC(s) can replace local (substation) processing. In this case Master Stations, located at central location, would be responsible for event file transfer from remote DFRs. The latter system has slower time response due to the time needed to transfer large uncompressed event files. [5 - 7]

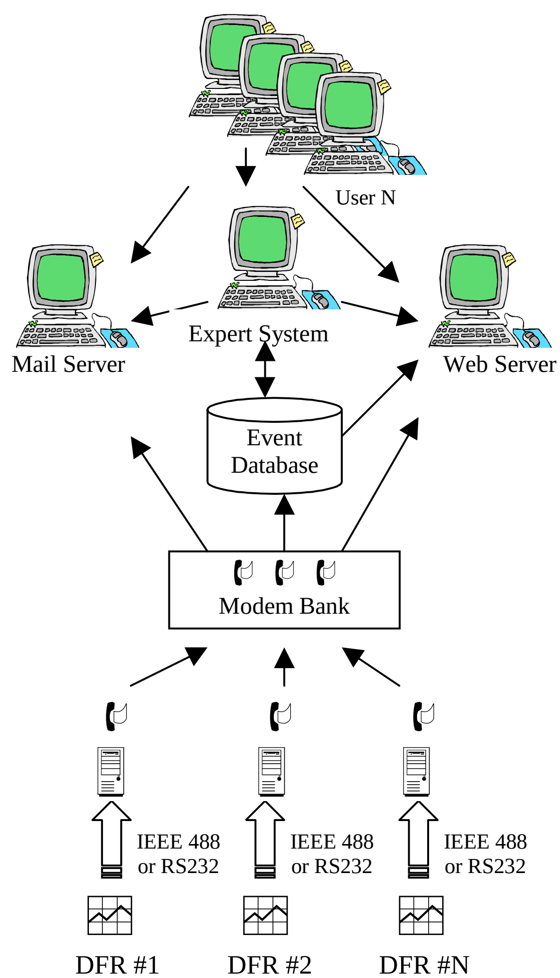

FIGURE 2. Generic block diagram for automated DFR file classification system

In addition to the Expert System PC, a corporate Mail Server, and Intranet Web Server are integral part of the proposed integrated classification system. Mail server is used for automated company-wide distribution of classification results via e-mails. Likewise, the Expert System interfaces with Intranet Web Server are used to automatically publish classification results containing analysis of DFR event as well as selected images of analog and digital traces.

The Event Database serves as a repository of DFR files, associated classification reports, and DFR configuration information. It contains both the original, 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.

The user can access the results of the Expert System's automated DFR file analysis using three methods:

- Web access using standard browser (e.g., Internet Explorer, or Netscape Navigator)
- Report Viewer
- Appropriate graphical viewing software provided by DFR vendor

The Report Viewer is separate universal viewing software package that provides an integrated environment for displaying both the conclusions about the analysis of a selected DFR file, as well as waveform graphics in the form of analog and digital traces.

The Expert System Application

One of the tasks of the Expert System is to reduce the time that system protection personnel spend on manual examination and archival of DFR records. When a fault condition exists, the system automatically classifies and filters DFR records based on the following broad criteria:

- Clearing time is satisfactory.
- Clearing time is longer than expected.
- Carrier misoperation occurs during fault clearing.
- Breaker abnormality occurs (slow clearing, restrike, or failure) during fault clearing.
- PT ferro-resonance occurs during fault clearing.

Table I outlines the DFR file signals that are utilized by 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.

TABLE I. Input signals used by the Expert System

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	(Ia, Ib, Ic)
	Residual current	(Ir)
	All three phase (bus side) voltages	(Va, Vb, Vc)
	Residual (neutral) voltage	(Vr)

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

- Relay trip duration (initiate and reset time)
- Breaker operate time (position open/close indication time)
- Breaker failure timer pickup duration (initiate and reset time)
- Carrier start/receive/stop duration times
- Calculated fault inception
- Calculated fault clearing time

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

- Slow relay clearing
- Breaker slow clearing, restrike, or failure
- Carrier misoperation
- PT Ferro-resonance
- Reclosure failure, or line lockout
- Bus clearing
- Normal fault clearing
- No operation (manual trigger)

The Fault Location Application

In addition to the analysis described, the system requirement is to calculate the fault location accurately. A suite of algorithms has been developed for this application including options for data to be taken from one or both ends of a transmission line. The accuracy of the algorithms is constrained with the availability of data, power system configurations and operating conditions. Further improvements are discussed in the next section.

APPLICATION OF ADVANCED DFR TECHNOLOGY TO FAULT ANALYSIS

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 they need to 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 [8, 9]. 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

Our survey of current DFR technology revealed that none of the existing off-the-shelf DFR models could support two-ended fault location algorithms without some modifications. Presently, the DFR is most commonly used to record the events after a trigger is initiated.

The proposed DFR developments are related to modification of an existing DFR to provide continuous recording synchronized with Global Positioning System (GPS) Satellite receivers. The GPS receiver signal is available today as an IRIGB time stamp, and is not used for high precision synchronized sampling. The proposed modification will allow for continuous recording of data so that a variety of events can be recognized and processed on the fly. This will enable high speed assessment of important events and potential use of this data for improved control by the system operators. High precision synchronized sampling will allow for direct correlation between data taken at two ends of a transmission line.

This modified DFR platform will enable implementation of several measurement applications such as high precision fault location and phase angle between two ends of the line. Such advanced measurements will provide additional capabilities for the automated analysis of DFR events that may include a variety of important system disturbances not related to a fault. Typical examples are variations in system frequency, violations of voltage and load limits, and power system oscillations affecting stability.

One of the most important requirements for fault location algorithm using synchronized sampling from two line ends 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. 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 [8,9]. In order to derive these equations we can consider the unfaulted long transmission line shown in Figure 3. 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

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

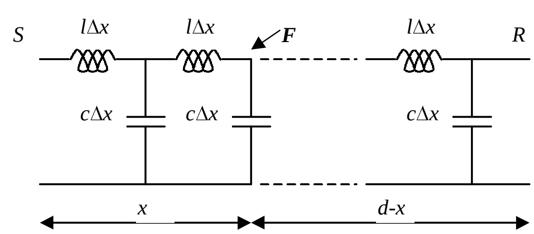

FIGURE 3. Unfaulted long transmission line

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 [8,9]:

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

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 the 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 [10].

AUTOMATED POWER QUALITY ASSESSMENT USING MODIFIED DFRs

Advanced DFRs can be utilized as a data acquisition system for applications in the area of power quality assessment. Digital fault recorders provide a set of programmable triggers (over-voltage, under-voltage, over-current, rate of change, etc.) that initiate capturing of data. Once triggered, DFR stores data record on a local hard drive where it can be accessed by other software (e.g., master station or automated analysis software).

These data records contain snapshot of recorded quantities (usually voltages, currents and relaying contacts) during disturbance. In addition, several cycles of prefault data are available by default.

DFR triggers, as presently implemented, may not necessarily operate for every case of disturbance that is of interest for power quality assessment. One such case may be triggering on a slow variation of load characteristics.

This shortcoming may be avoided by using the analysis system illustrated in Figure 4. The system consists of a digital fault recorder and external PC. Two units are connected via high-speed parallel communication link. A digital fault recorder serves as a data acquisition front-end, providing continuous data flow toward the monitoring system PC. At the same time, DFR maintains its basic function of recording the events according to the internal triggers and storing those events on the local hard drive inside the recorder. These stored events are available remotely per request over a dial-up line, using master station software provided by the DFR manufacturer.

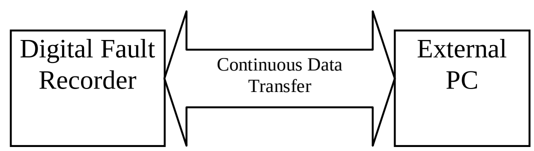

FIGURE 4. Block diagram of power quality analysis system

Continuous data stream from the DFR is divided into blocks of fixed size. These data blocks are time tagged and queued at a prespecified memory location on a PC side. Signal processing algorithms that are part of the power quality assessment software access and process these incoming data blocks in real-time. These algorithms are similar to DFR internal triggers, but involve more extensive and complex computation.

Implementation of the system shown in Figure 4 is straight forward and has been developed for a different application [11]. The algorithms for power quality assessment are also quite easy to implement using advanced signal processing techniques [12,13].

Further extensions of the fault analysis system described earlier to accommodate the power quality analysis are obvious and can be implemented easily.

CONCLUSIONS

This paper illustrates the following trends in the future developments of DFR based systems for automated analysis of disturbances and protective relay operations:

- Existing DFR infrastructure with communication capabilities and centralized master stations can be enhanced with new software to provide automated analysis of faults and related equipment operations.
- Existing DFRs can be further modified to allow synchronous sampling using reference time signals from GPS receivers allowing for development of an accurate fault location using data from two ends of a transmission line.
- Further modifications of DFRs can be pursued to enable continuous monitoring of power system disturbances providing the required platform for implementation of an automated system for power quality assessment.

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