

Automating the Analysis of Faults and Power Quality

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

munication services are also implemented to facilitate storing, viewing, and distributing of the analysis reports.

The second part of the article 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 Global Positioning System (GPS) satellite-controlled sampling of the input data are proposed.

The last part of the article points out how the automated fault analysis and synchronized sampling technologies can be extended to the monitoring of power quality disturbances. Further modifications of the DFR are proposed to allow for con-

tinuous monitoring of the events. A variety of digital signal processing algorithms for power quality monitoring and analysis are referenced.

Intelligent systems and advanced signal processing techniques are used in the automated analysis of disturbances and protective relay operations

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 article introduces an advanced system for automated fault analysis, accurate fault location, and extensive power quality monitoring based on the DFR infrastructure. 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 article 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 in a central location. A variety of com-

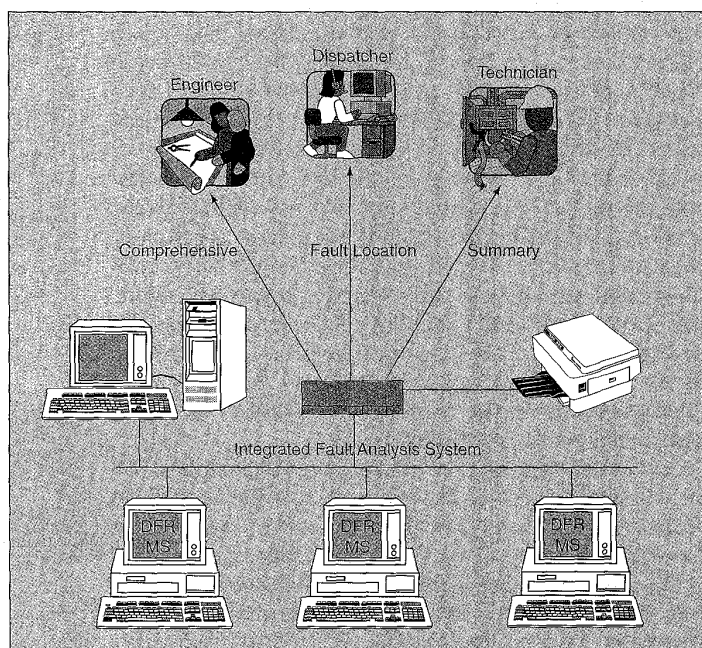


Figure 1. Major user groups and levels of information requested by each group

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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 a fault analysis system (see Figure 1). Protection engineers are interested in getting detailed and specific information regarding the operation of the protection system and related equipment during an event. Technicians require a summary of the fault classification to help them troubleshoot incorrect operations of protection equipment. System dispatchers are interested in getting condensed fault analysis information as soon as possible after the occurrence of a fault. The dispatchers' main interest is determination of accurate fault location and switching equipment status that enables them to make decisions about the system restoration.

The integrated fault analysis system featured in this article can be built with existing technology and can satisfy all three groups of users: protection engineers, technicians, and system dispatchers.

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. The system is based on client/server architecture. The server side consists of an expert system PC, an 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 links, process event files locally, perform file compression, and finally upload results to the expert system for further processing and archiving. This ensures that the time from event recording until the analysis is available at a central location is short and system's response is suitable for use by dispatcher. Optionally, dedicated master station PCs can replace local (substation) processing. In this case, the master stations, located at a central location, would be responsible for event file transfer from remote DFRs. The latter system has slower response time due to the time needed to transfer large uncompressed event files.

In addition to the expert system PC, a corporate mail server and an Intranet Web server are integral parts of the proposed integrated classification system. The mail server is used for automated company-wide distribution of classification results via E-mail messages. Likewise, the expert system interfaces with the Intranet Web server are used to publish automatically classification results containing analysis of a DFR event as well as selected images of analog and digital traces.

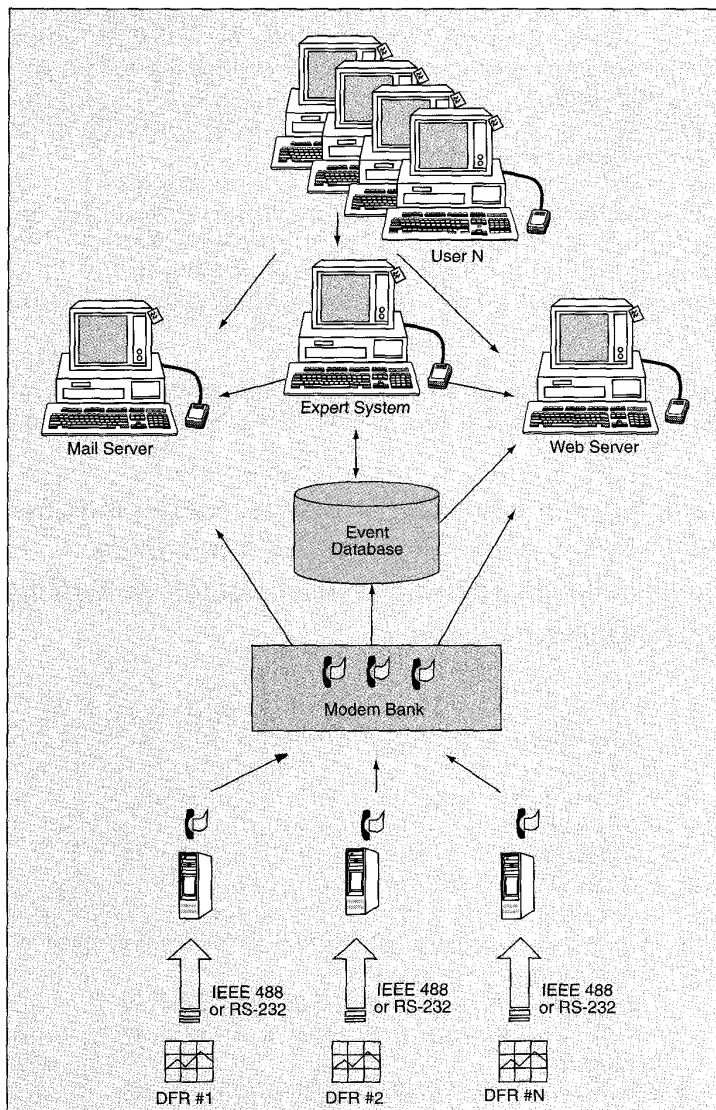


Figure 2. Generic automated DFR file classification system

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 COMTRADE format. 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.

Users can access the results of the expert system's automated DFR file analysis using three methods:

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

Report Viewer is a separate universal viewing software package that provides an integrated environment for dis-

playing conclusions about the analysis of a selected DFR file, as well as waveform graphics in the form of analog and digital traces.

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 archiving 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,

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 ferroresonance
- Reclosure failure or line lockout
- Bus clearing
- Normal fault clearing
- No operation (manual trigger).

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 as follows.

A fast, reliable, and accurate data acquisition system is required for a fault-location algorithm that uses synchronized sampling from two line ends

restrike, or failure) during fault clearing.

- PT ferro-resonance occurs during fault clearing.

The following DFR file signals are utilized by the DFR file classification logic:

- Digital: primary and back-up relay trip, breaker open position, breaker close position, breaker failure (BF) contact, carrier start and carrier received contacts
- Analog: at least two phase currents (I_a , I_b , I_c), residual current (I_r), all three phase (bus side) voltages (V_a , V_b , V_c), residual (neutral) voltage (V_r)

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 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 these

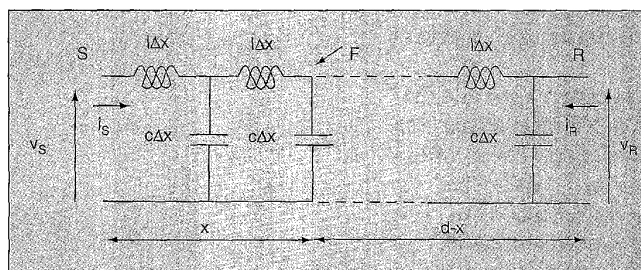


Figure 3. Unfaulted long transmission line

Application of Advanced DFR Technology to Fault Analysis

As noted earlier, accurate and timely information regarding fault location, after a transmission line fault has occurred, is most

important to system dispatchers. They must confirm and isolate the faulted section before any system restoration is attempted, and then they must dispatch maintenance crews directly to the fault site.

Most existing fault-location algorithms use data from one line end, due to the large cost of additional equipment involved in obtaining data from the other end as well. Recently, the cost of the necessary hardware has been decreasing rapidly, which makes implementation of two-ended fault-location algorithms cost effective for critical transmission lines. 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.

Proposed DFR developments are related to modification of an existing DFR to provide continuous recording synchronized with GPS 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 system operators. High-precision synchronized sampling will allow for a 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 a 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. 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:

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

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

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

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

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_{dx} , 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:

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

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 nonzero 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 cou-

High-precision synchronized sampling allows for a direct correlation between data taken at two ends of a transmission line

pled lines if synchronized measurements are available from the terminals of the coupled lines.

Automated Power Quality Assessment Using Modified DFR

Advanced DFRs can be utilized as a data acquisition system for applications in the area of power quality assessment. DFRs 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 the 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 a snapshot of recorded quantities (usually voltages, currents and relaying contacts) during the 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 an external PC. Two

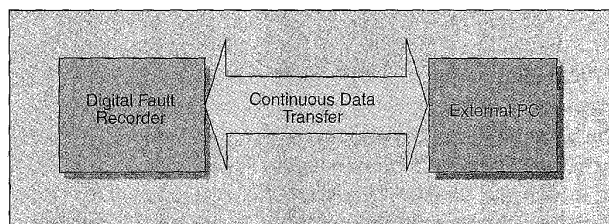


Figure 4. Power quality analysis system

units are connected via a 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, the 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.

A 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.

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 straightforward and has been developed for a different application. The algorithms for power quality assessment are also quite easy to implement using advanced signal processing techniques.

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

Acknowledgments

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For Further Reading

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Biographies

Mladen Kezunovic received his Dipl. Ing. degree from the University of Sarajevo, and MS and PhD degrees from the University of Kansas, all in electrical engineering, in 1974, 1977, and 1980, respectively. His industrial experience is with Westinghouse Electric Corporation in the USA, and the Energoinvest Company in Sarajevo. He also worked at the University of Sarajevo. He was a visiting associate professor at Washington State University in 1986-1987. He has been with Texas A&M University since 1987 where he is a professor and director of the Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for relay testing as well as application of intelligent methods to power system monitoring, control, and protection. He is an IEEE Senior Member and a registered professional engineer in Texas.

Igor Rikalo received his Dipl. Ing. degree from the University of Sarajevo and MS degree from Texas A&M University, both in electrical engineering, in 1992 and 1994, respectively. Currently, he is working for TLI, Inc. as a senior systems engineer and for Texas A&M University as a research engineer. He is completing the MBA program at Texas A&M University. He has worked in the area of intelligent system applications to the power industry since 1992.