AUTOMATED FAULT ANALYSIS USING ADVANCED INFORMATION TECHNOLOGY FOR DATA INTEGRATION AND INFORMATION EXCHANGE

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Summary: This paper addresses some new approaches to data integration and information exchange that are made possible due to the use of advanced Information Technology (IT). As a result, some traditional applications such as fault analysis can be significantly enhanced and automated. Paper first describes how the functional enhancement and automation of fault analysis may result in faster system restoration, better quality of power delivery, and more comprehensive preventive maintenance actions. The paper illustrates how in the competitive utility environment this leads to improved service and ultimately better customer satisfaction while maintaining and even reducing operational cost. Several examples related to automated fault analysis are described as follows: disturbance analysis, analysis of Circuit Breaker (CB) operation, and fault location analysis using sparse field data.

Keywords: Automated Fault Analysis-Fault Location-Modeling and simulation-Maintenance-Power Quality-Information Technology.

INTRODUCTION

Deregulation, liberalization, restructuring and privatization in the utility industry are simultaneously happening around the globe. They represent different approaches to making the utility industry more cost effective and responsive to customer needs.

As a result, two important trends are recognized: the introduction of more automated functions and the use of more advanced information technology. The final aim is to provide better service to the customers and to reduce the operating cost.

This paper illustrates how the existing fault analysis approach can significantly be enhanced through the use of advanced information technology [1]. In this context, the information technology relates to the technology for communications, processing, intelligent systems, computer networks, databases, user interfaces, etc. First, the application functions can be improved to include broader view of the analysis including data from multiple intelligent electronic devices (IEDs). This leads to a comprehensive data integration resulting in efficient data processing. Once the relevant information is extracted, it can be distributed to multiple users responsible for maintaining the quality and reliability of the energy supply service. All of this can easily be automated using information technology services embedded in the applications.

To illustrate the expected benefits of the use of information technology to support fault analysis automation through data integration and information exchange, several implementations carried out by the authors are presented. The examples include: comprehensive fault and power quality disturbance analysis, enhanced just-in-time analysis of circuit breaker operation, and improved fault location analysis using modeling, simulation and field data. [2-4].

The paper first gives the background of the enhanced fault analysis approach based on data integration and information exchange. The use of information technology to automate the analysis based on data integration and information exchange is covered next. Conclusions and references are given at the end.

ENHANCED FAULT ANALYSIS BASED ON DATA INTEGRATION AND INFORMATION EXCHANGE

Traditional fault analysis is based on the use of Digital Fault Recorders (DFRs) . The records are brought to the Master Station located at the Engineer's office, and then the analysis is done manually going through the records one at the time. Depending on the triggering methods used to record field data, DFRs may be recording both faults and other similar events activating the triggers such as power quality disturbances, switching transients, spurious noise interferences, etc. This makes the analysis rather tedious since many of the opened data records may not contain information relevant to fault analysis. In addition, data from DFRs is rather limited providing analog and contact signals from a given substation with no correlation to the data recorded by other Intelligent Electronic Devices in this and other substations across the system.

The latest developments in the substation automation area have enabled the use of multiple IEDs on the same local Area Network (LAN) while all the devices in a given substation can be accessed using the same communication protocol [6]. In addition, the Internet services are extensively used to provide system-wide exchange of data and information. This allows one to

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include data from multiple IEDs in defining and implementing the fault analysis function.

A new approach featuring data integration and information exchange is illustrated in Fig. 1. Data may be obtained from several types of IEDs such as digital fault recorders (DFRs), digital relays (DRs), power quality (PQ) meters, remote terminal units (RTUs), sequence of event recorders (SERs), programmable logic controllers (PLCs), circuit breaker monitoring (CBM) devices, etc. Enhanced fault analysis is an example of the application that relies on this approach. It may be noted that the analysis is somewhat broader than traditionally defined in that it includes analysis of both fault and power quality disturbances as well as detailed analysis of operation of breakers and relays.

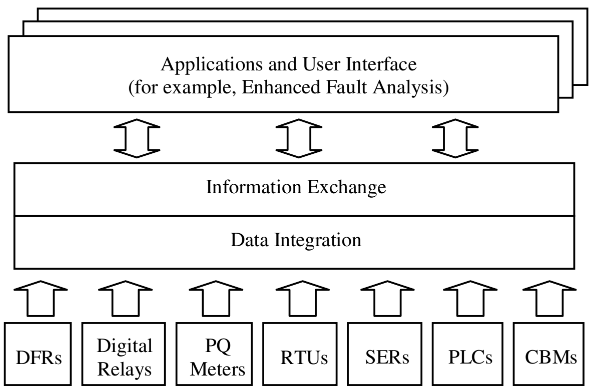

Fig. 1. Data integration and information exchange

It may be noted that selected IEDs in the figure provide detailed information about:

- Power quality disturbances
- Fault type and location
- Operation of protective relays
- Operation of circuit breakers

This information has to be extracted from the recorded data provided by separate IED types and integrated for this purpose. The collection of data, its integration and processing need to be done automatically. Once the data is processed the obtained information needs to be packaged in appropriate reports to serve several different groups in the utility:

- Managers responsible for reliability and efficiency of the system operation
- Protection engineers responsible for correct operation of the relays and related fault clearing equipment
- Maintenance crews responsible for performance of the circuit breaker operation
- Customer service representatives responsible for quality of power supply and fulfillment of power delivery contracts
- Dispatchers responsible for locating the faults and restoring the system operation

All the mentioned groups can benefit from the data collected by various IEDs given in Fig. 1 as long as there are means for automating the data integration, processing, and analysis as well as exchanging the analysis reports, historical data and user requests. This enhanced functionality is made possible through the use of the IT solutions readily available on the market, and appropriately imbedded in the mentioned applications. The following sections give an overview of several advanced applications that have used IT services to perform the automation and user interfacing services.

AUTOMATED DISTURBANCE ANALYSIS

Fault Analysis

The main goal of this analysis is to detect the fault, identify the fault type, and assess the performance of relays, communication schemes and circuit breakers involved in the fault clearing.

A solution that has been installed is used to illustrate how the IT technology has been embedded with the automated fault analysis to provide an integrated solution [2]. The design requirement for this solution is centered on the need to connect DFR Master Stations (MSs) located in multiple service centers using the Internet technology. In addition, each service center has a variety of MSs produced by different vendors, each connected to several DFRs from related vendor. The final solution is shown in Fig. 2.

The analysis enables reaching the following conclusions:

- Fault type and location
- Performance of relays, communication channels and circuit breakers
- Occurrence of ferroresonance conditions and autoreclosing sequences

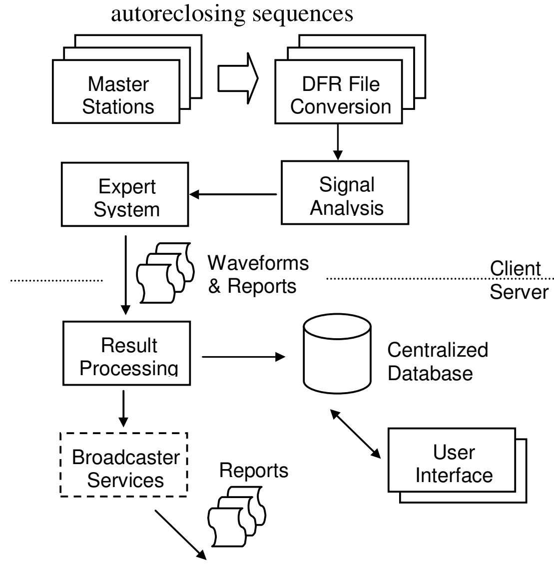

Fig. 2. Automated fault analysis using DFRs and MSs from multiple vendors.

Typical analysis report display is shown in Fig. 3. The following information is provided in each report:

- Original field recorded data
- Results of the analysis
- Substation configuration data
- Historical data and report search options

The use of IT imbedded with the application allows the following enhanced user functions:

- Retrieving the data and reports using web browser services
- Disseminating the analysis results through fax modem, pager, and email broadcast services
- Maintaining the database and user interface settings through straightforward means

This solution has shown some major benefits when compared with the traditional approaches. The comparison is shown in Table I.

Table I. Comparison of traditional and enhanced fault analysis approaches

Characteristics	Traditional	Enhanced
Mode of analysis	Manual	Automatic
Data storage	Dedicated, device specific	Centralized database, universal
Dissemination of reports	Manual, hardcopy	Automatic, email, fax, web
Instruments used	DFRs and/or DRs	Any IEDs
User interface	Dedicated, device specific	Universal, device transparent

Power Quality Analysis

The main goal of the analysis is to assess the PQ disturbances automatically and to identify the ones that are caused by faults (voltage dips) [3].

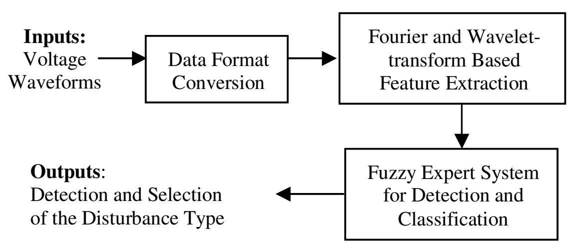

Fig. 4. Disturbance detection and classification

The flowchart of the proposed solution for PQ event detection and classification is shown in Fig. 4. The sub-module "Data Format Conversion" converts the inputs from a specific recording device or simulation package format into a common data format comprehensible to other modules of the software. The "Fourier and Wavelet-transform Based Feature Extraction" module obtains unique features pertinent to specific events and "Fuzzy Expert System for Detection and Classification" module reaches a decision regarding detection and classification, as discussed next [3].

FFT and wavelet-analysis based feature extraction. The following eight distinct features inherent to different types of power quality events have been identified: the Fundamental Component (V_n), Phase Angle Shift (α_n), Total Harmonic Distortion (THD_n), Number of Peaks of the Wavelet Coefficients (N_n), Energy of the Wavelet Coefficients (EW_n), Oscillation Number of the Missing Voltage (OS_n), Lower Harmonic Distortion (TS_n), and Oscillation Number of the rms Variations (RN)[3].

Fuzzy expert system for detection and classification. The core of the rule set of the implemented fuzzy expert system is illustrated as follows:

a) Detection: For detection, one rule is used as follows:

Rule 1: if THD_n is A_2 **or** PS_n is B_2 **or** V_n is C_3 **or** V_n is C_1 then DETECT=1

b) Classification: fifteen rules are used as follows:

Rule 1: V_{n+1} is A_4 and N_n is F_1 and OS_n is G_1 then IMPULSE=1

Rule 2: V_n is A_1 or V_{n+1} is A_1 then INTERRUPTION =1

Rule 3: V_n is A_6 or V_{n+1} is A_6 then SWELL=1

Rule 4: V_n is A_5 and PS_n is C_1 and PS_{n+1} is C_1 and EW_{n+1} is D_1 and { TS_{n+1} is H_2 or [TS_{n+1} is H_4 & TS_{n+2} is H_1]} then SWELL=1

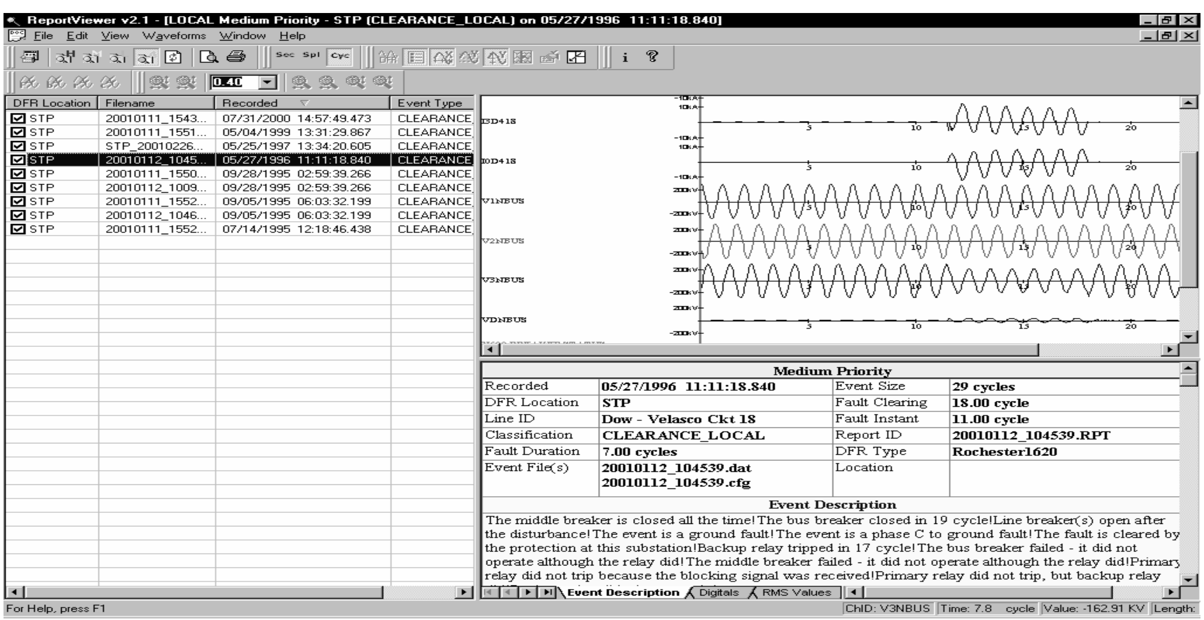

Fig. 3. User display in automated analysis systems

Rule 5: V_{n+1} is A_5 and { PS_n is C_2 or PS_{n+1} is C_2 } then SWELL=1

Rule 6: V_{n+1} is A_2 then SAG=1

Rule 7: V_{n+1} is A_3 and { PS_n is C_2 or PS_{n+1} is C_2 } then SAG=1

Rule 8: V_{n+1} is A_3 and { PS_n is C_1 and PS_{n+1} is C_1 } and { THD_{n+1} is B_1 or [THD_{n+1} is B_2 and OS_{n+1} is G_4]} then SAG=1

Rule 9: V_{n+1} is A_3 and PS_n is C_1 and PS_{n+1} is C_1 and OS_n is G_2 and THD_{n+1} is B_2 and THD_{n+2} is B_2 and THD_{n+3} is B_2 then NOTCH=1

Rule 10: V_{n+1} is A_3 and N_n is F_2 and OS_n is G_2 then NOTCH=1

Rule 11: V_{n+1} is A_4 and PS_n is C_1 and PS_{n+1} is C_1 and THD_n is B_3 and THD_{n+3} is B_1 and { OS_n is G_4 or OS_{n+1} is G_4 } then TRANSIENT=1

Rule 12: V_{n+1} is A_4 and TS_{n+1} is H_3 and TS_{n+2} is H_3 and TS_{n+3} is H_3 and OS_{n+1} is G_4 then HARMONIC=1

Rule 13: THD_{n+1} is B_4 and THD_{n+2} is B_4 and THD_{n+3} is B_4 and OS_{n+2} is G_4 then HARMONIC=1

Rule 14: TS_{n+1} is H_4 and TS_{n+2} is H_4 and TS_{n+3} is H_4 and OS_{n+2} is G_4 then HARMONIC=1

Rule 15: If RN is K_1 then FLICKER=1

In the above rules, $A_{i,}\ B_{i,}\ C_{i,}\ D_{i,}\ F_{i,}\ G_{i,}\ H_{i,}$ and K_i are the membership functions for the input patterns, where the common trapezoidal and triangular functions are used [3]

The fuzzy partitions and the corresponding membership functions can be obtained based on both the statistical studies and expert's knowledge. Opinions from operators can be conveniently incorporated into the system in practical applications.

The output for the detection part is the variable "Detect" whose value reflects the credibility that certain disturbance exists. The outputs for the classification parts are fuzzy variables "Flicker", "Impulse", "Interruption", "Swell", "Sag", "Notch", "Transient", and "Harmonic" whose values represent the degree to which the event belongs to each of these categories. The type of the event selected will be the one with the largest membership. In cases where two or more types of disturbances have the same largest membership value, all of them will be selected for further analysis. Evaluation studies demonstrated a correct identification rate of 99%.The corresponding characterization algorithms can be selected for extracting more accurate and pertinent parameters.

In the context of fault analysis, if the sag is characterized as "caused by a fault", this conclusion triggers an extended fault analysis that searches for the location of the fault, as described later on in the fault location analysis section.

Circuit Breaker Operation Analysis

The main objective is to analyze circuit breaker (CB) operation performance each time it operates. Detailed analysis of the breaker operation is enabled by monitoring of additional control signals related to CBs and with an extensive rule-based expert system [4]. This analysis also identifies several breaker operation features thus pointing to potential failures in future.

The system architecture and basic software modules are show in Fig. 5 [4]. The system architecture is typically split between two locations: the substation where data are recorded during breaker testing and the central repository where data from all tested breakers are gathered.

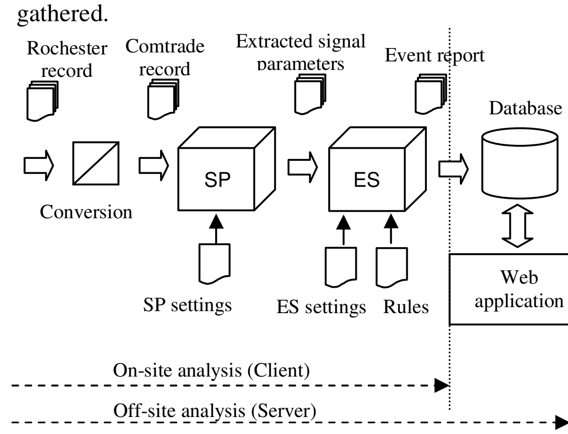

Fig. 5. Functional description of the analysis software

In the particular case, Rochester recorder is used for monitoring the CBs. After the data format conversion, the analysis software performs signal processing (SP) in order to extract several features and parameters relevant to the operation of CBs. This module extracts pertinent signal parameters from recorded signals using advanced processing methods such as: wavelet analysis, Fourier analysis and digital filtering. The extracted parameters are then processed by a rule-based expert system (ES), which is a decision making system emulating reasoning of a human expert. Around one hundred rules are used in this particular solution. The client part of the application is used on-site (in substations). The server application is installed in the centralized office and, in addition to the analysis, maintains the centralized database and provides an extensive web based user interface. The server is typically connected to the corporate intranet. There is an option to upload DFR files to the server from any computer connected to the company intranet. Web application (Fig. 7) enables easy manipulation of data and reports as well as additional tools for manual analysis by experts.

In the context of the extended fault analysis, the CB analysis can be triggered each time the relay or DFR initiate/detect an operation of the breaker. In that case, the CB monitoring system can provide additional details about the CB operation and can alert both protection engineers and maintenance crews about related details.

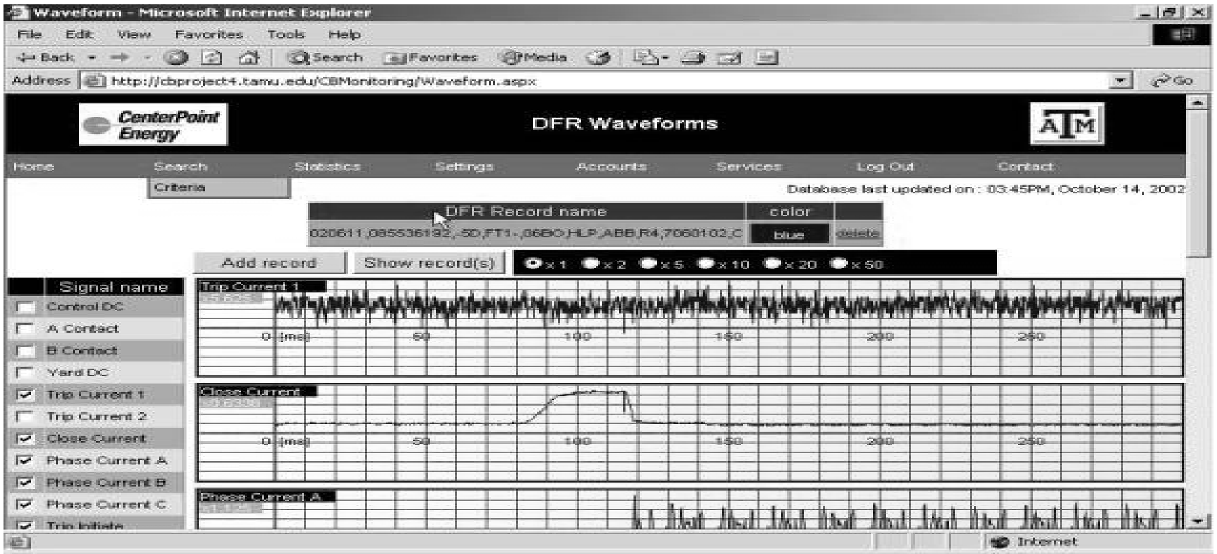

Fig. 6. CB analysis web-based user interface

FAULT LOCATION ANALYSIS USING SPARSE FIELD-RECORDED DATA

The proposed approach makes use of the "waveform matching" based methodology. The two key concepts, namely the "sparse data" and "waveform matching" are illustrated as follows [5].

Sparse data are the data obtained from recording devices sparsely located at various substation locations. Examples of recording devices may include digital fault recorders (DFR), digital relays, or other intelligent electronic devices (IED). The data captured by recording devices may include analog quantities such as voltage and current waveforms and digital (contact) quantities such as breaker status and relay operation status. Both analog and digital quantities may be useful for locating the fault. To solve the fault location problem utilizing sparse data, the "waveform matching" based approach may be used.

The model of the power system is utilized to carry out simulation studies. The matching is made between the voltage and current waveforms captured by recording devices and those generated in simulation studies. The fault is searched through the system model by utilizing an iterative search process. The search process may consist of the following steps. First an initial fault location is assumed. Second, the simulation studies are set up according to the specified fault. Third, the simulation studies corresponding to the specified fault are carried out utilizing appropriate simulation tools. Fourth, simulated waveforms of interest are obtained. Fifth, the simulated waveforms are compared with recorded ones, and the matching degree of the simulated and recorded waveforms is evaluated by using appropriate criteria. Sixth, the initial fault location is modified according to predefined strategy, and then the process proceeds to the second step and continues. The above steps are iterated until the simulated waveforms that best match the recorded ones are produced. The fault location will be determined as the one specified in the simulation model used for generating the simulated waveforms that best match the recorded ones .

The fault location problem can be formulated as an optimization problem: Find the value of x and R_f that minimize:

$$f_c(x, R_f) = \sum_{k=1}^{N_v} \{| V_{ks} - V_{kr} |\} + \sum_{k=1}^{N_i} \{| I_{ks} - I_{kr} |\} \quad (1)$$

or maximize

$$f_f(x, R_f) = -f_c(x, R_f) \quad (2)$$

where

$f_c(x, R_f)$: defined cost function

$f_f(x, R_f)$: defined fitness function. The larger the value of the fitness function, the better the matching of the simulated and recorded phasors, and better the solution is.

x : the fault location, R_f : fault resistance

V_{ks} and V_{kr} : "during-fault" voltage phasors obtained from short-circuit simulation studies and from recorded waveforms respectively.

I_{ks} and I_{kr} : "during-fault" current phasors obtained from short-circuit simulation studies and from recorded waveforms respectively.

k : index of the voltage or current phasors

N_v and N_i : total number of the voltage and current phasors respectively.

It is noted that the largest possible fitness value defined by equation (2) is equal to zero and can be reached if the phasors obtained from simulation studies exactly match those obtained from recorded waveforms. Therefore, the best fault location estimate would be the one that maximizes equation (2). It has been shown that the fitness surface obtained for various fault location and resistance values is not regular and contains saddle points and local maximum points. It is rather difficult to use the gradient-based method to find the global maximum point. Exhaustive search through every possible solution may also be too time-consuming to be practical .

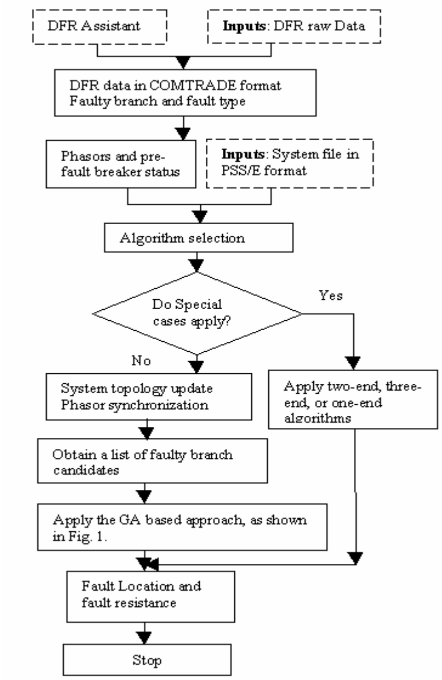

Fig. 7. Overall architecture of the software modules

The GA based optimization approach is good at finding the globally optimal solution and avoiding the local optima. The nature of the fitness function prompts the attempt of the GA based optimization method as described next [5].

The overall architecture of the developed software is shown in Fig. 7. DFR Assistant [7] converts the DFR raw data into COMTRADE format [8] and obtains the fault type and faulty branches based on individual DFR recording. Based on such information, the phasors of the monitored voltage and current quantities, and pre-fault breaker status can be obtained. Based on the topology data and a number of measurements available, the fault location software determines the type of the fault location algorithm to be utilized. If special cases like two-end, three-end, one-end algorithms apply, the fault location can be obtained directly based on the related voltage and current phasors without running any PSS/E [9] simulation studies. If the case belongs to the general sparse-data case, then the following steps are to be taken.

(1) The current phasors and/or the pre-fault breaker status can be utilized to tune the system topology (update the static system model). Only the service status of the branch is updated. If the magnitude of the pre-fault current phasor of the monitored branch is smaller than a pre-specified value, then the branch is considered as being out of service. Branch status is also updated according to the pre-fault breaker status. If both the pre-fault breaker status and the current of a branch are monitored, the recorded current overrules the breaker status for determining the service status of the branch .

(2) After the system topology is updated, the PSS/E load flow study is carried out to obtain the pre-fault phasors of the related bus voltages and branch currents. Then the phasors derived from the recorded waveforms are synchronized by rotation with reference to the phasors obtained by the load flow study.

(3) Based on the faulty branches given by DFR Assistant and the system topology, the software derives the list of total faulty branch candidates for posing faults.

(4) The GA algorithm based approach is activated for searching the fault locations.

CONCLUSIONS

Based on the discussion, the following is concluded:

- Data integration and information exchange enables enhanced fault analysis
- Many different utility groups may benefit from the enhanced fault analysis
- Information technology is essential for automating the analysis, data and report retrieval, and user interfacing

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