

Selection of Optimal Fault Location Algorithm

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Abstract—Once fault event in power system occurs different Intelligent Electronic Devices (IEDs) automatically recognize the fault as abnormality. With technological development many IEDs available today are capable of recording, executing analysis automatically and communicating results to different locations. Although recording capabilities are drastically increased applications that would fully utilize recorded data are still not available. In this paper, automated fault location (FL) procedure and usage of different intelligent algorithms is presented. Data is retrieved from various data sources, processed using expert system, neural networks, and genetic algorithm in order to provide data for optimal FL algorithm selection.

Index Terms—expert system, fault location, genetic algorithm, intelligent electronic device, neural network, power system monitoring, substation measurement, sampling synchronization.

I. INTRODUCTION

Various types of FL algorithms have been developed in the past [1-6]. Depending on availability of recordings with respect to the location of a given fault the use of different FL algorithms is possible. In order to be able to evaluate which algorithms are applicable, analysis must take into account both temporal and spatial considerations [7]. Fig. 1 shows system architecture of such analysis. In [8] a solution in which recordings from different Intelligent Electronic Devices (IEDs) are automatically transferred to central repository is proposed. In the rest of the paper we will assume that such repository of Digital Fault Recorder (DFR) data is available.

First, architecture used for implementing selection of optimal FL algorithm is presented. It shows relations between input data and corresponding algorithms. Second, utilizing expert system for analysis of recording from single DFR is discussed. Then, synchronized sampling two-end fault location is described and usage of neural networks (NN) for classifying faults and selecting a section where the fault may be is presented. System-wide sparse measurement approach and use of genetic algorithm (GA) in this approach is explained next.

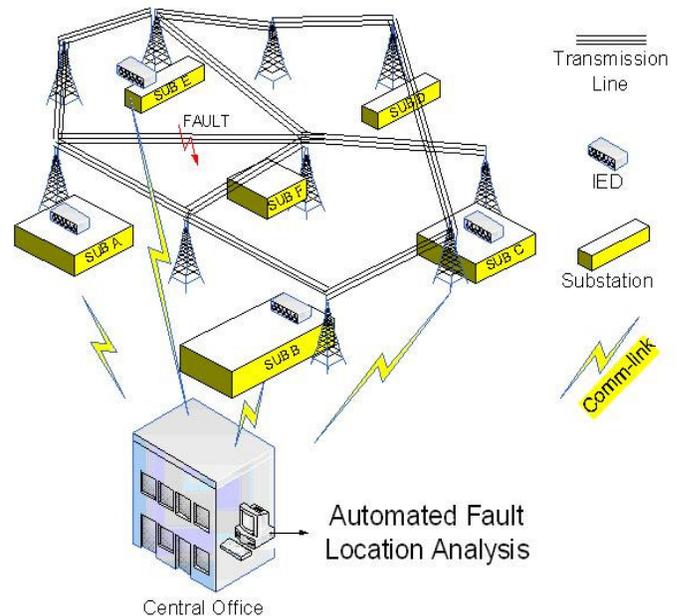


Fig. 1. System architecture

II. ARCHITECTURE OF PROPOSED SOLUTION

Since proposed solution should be able to use different FL algorithms it is necessary to provide different external tools in order to achieve the optimal performance of each algorithm. Architecture of the solution is shown on Fig. 2.

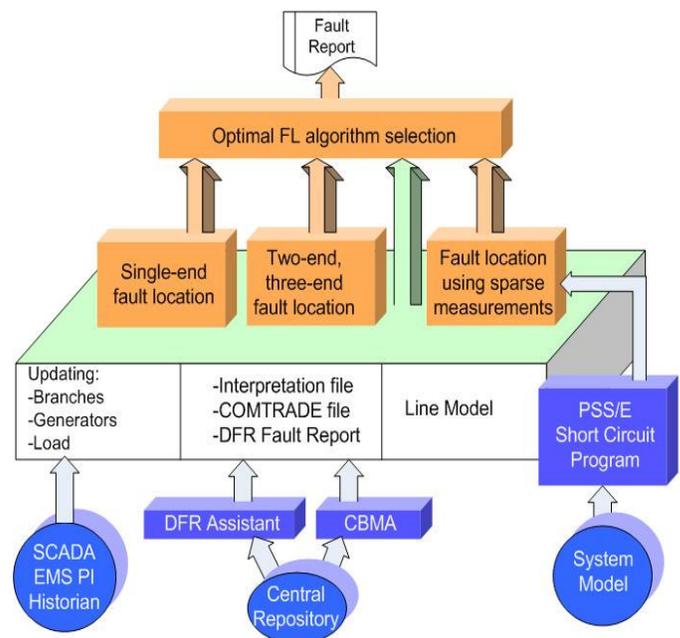


Fig. 2. Architecture of the proposed solution

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FL module updates power system status with retrieved data, processes new event files and runs the most suitable FL algorithm. With respect to the placement of measurements, three types of FL algorithms are used: one-end, multi-end and system-wide sparse measurements algorithms [1-6]. While processing new events and executing FL algorithms different intelligent techniques are used. Some of them will be presented in more details later.

External tools module consists of:

- SCADA EMS PI Historian used for obtaining the latest load, branch and generator data in order to update system model before FL calculation starts.
- DFR Assistant [9] provides new event recordings from central repository in COMTRADE format [10] and preliminary fault report. Report describes behavior of protection equipment, recognizes type of fault and it is used by other algorithms as input file.
- PSS/E Short Circuit program [11] is accessed during fault calculation by some algorithms in order to run power flow and short circuit analysis automatically.
- System model in PSS/E format is updated before any calculation starts in order to reflect system state prior to a fault. This is very important feature especially if topological changes took place in the mean time.
- Automated analysis application for Circuit Breaker Monitor (CBM) data provides new circuit breaker (CB) event recordings to a central repository in COMTRADE format [10], as well as the expert system report about the CB operation [12]. An application of the system wide data analysis that makes possible to track the circuit breaker switching sequences is demonstrated in [13]. This can be used for determining faulted section. Additionally it is possible to utilize CBM data to determine precisely when the fault happened and tune the system model to that time instance by updating corresponding generator, load and topology values with the data obtained from EMS PI Historian archive.

It may be noticed from Fig. 2 that proposed solution has modular architecture, which enables expanding this solution with additional segments. Processing additional data collected from other IEDs would provide more information about protection equipment that has operated. This information could be very useful for reducing possible fault location search area; understanding nature of the fault, and it could provide redundant data which could increase reliability and accuracy of results.

III. GENERATION OF PRELIMINARY FAULT REPORT USING EXPERT SYSTEM

Before selecting optimal FL algorithm it is necessary to process events data to find out possible faulted circuits, type of fault, what was sequence of events and was it correct, etc. An expert system has been developed to carry out the fault analysis based on recorded data describing the operations of the relay, relay communication channels behavior, and circuit breaker contact signal changes [14, 15].

After recording of a new event is made available signal processing module extracts relevant parameters. They are later passed to an expert system module which contains user defined rules which represent expert system knowledge about specific operation. In the case of fault detection and type classification, expert system knowledge can be expressed as mathematical relationship between certain parameters as shown on Fig 3. Expert system is implemented using CLIPS [16] engine which is embedded in the application.

In the proposed approach DFR Assistant investigates DFR recording and automatically generates preliminary fault report [8]. DFR Assistant performs analysis using data from individual substations. In the case that multiple DFRs were triggered due to a fault, DFR Assistant will process data files from each of them separately without correlating whether they belong to the same fault event or not. Automated FL procedure should be able to correlate the data in time and space and decide whether they belong to the same fault event. By using CB status data analysis from the system level, faulted lines could be identified and the selection could be compared with information from the corresponding DFR reports. If the DFR location, estimated faulted line from DFR Assistant report, and the timings of event match with corresponding faulted line recognized using analysis of the CB status data, automated analysis should pick the involved recordings, generated reports and continue with investigation.

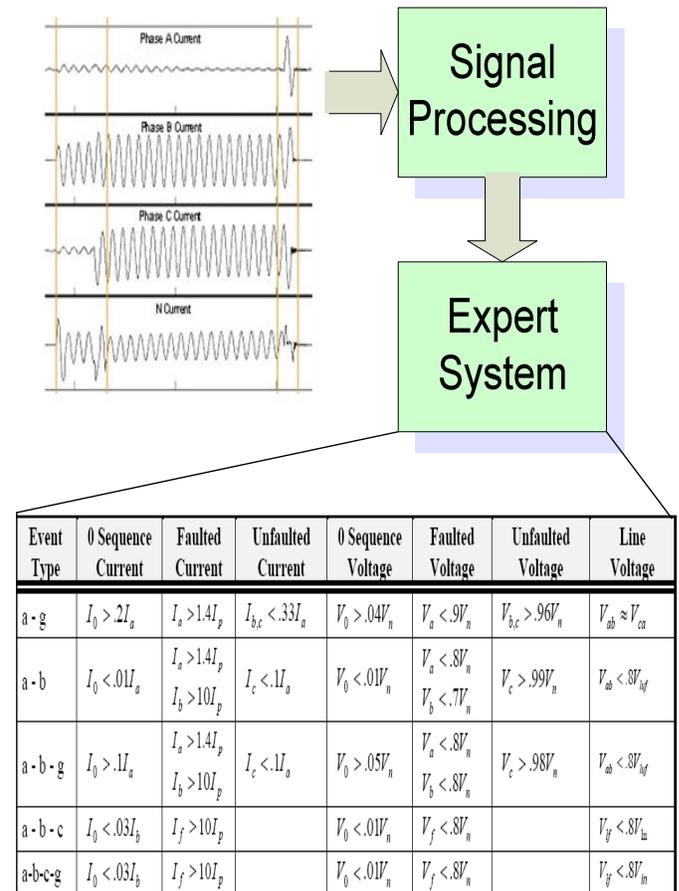


Fig. 3. Usage of expert system for preliminary fault report

IV. SYNCHRONIZED SAMPLING TWO-ENDED ALGORITHM

In [2] FL using synchronized sampling at two ends of a transmission line is presented. This algorithm does not depend on any unknown setting, which makes it very robust, and results are very accurate (obtained error is 0.5% in most cases [2]). This method is used as off-line tool for calculating FL. If used as the protective relaying application, it must be executed in real-time. Because of this, a trade-off between the accuracy and speed of decision is made. In order to improve both relaying (real-time) and fault location (off-line) decision-making, the authors propose enhancing application of synchronized sampling two-end FL algorithm by introducing technique for fault detection and classification based on a specific neural network [17].

A. Algorithm Description

The approach of synchronized sampling at two ends of a transmission line belongs to time based methods and it uses either lumped and distributed parameter model depending on transmission line length. This algorithm is based on fact that the voltages and currents from one end of the faulted line can be expressed in term of the voltages and currents of the opposite end. So in case that fault occurs at some point x on transmission line as Fig. 4 shows we have [2]:

$$v_F = L^v \{v_S, i_S, d - x\} \quad (1)$$

$$v_F = L^v \{v_R, i_R, x\} \quad (2)$$

By combining (1) and (2) we get:

$$L^v \{v_S, i_S, d - x\} - L^v \{v_R, i_R, x\} = 0 \quad (3)$$

Where,

v_s, i_s, v_r, i_r are vectors of voltages and currents of the sending and receiving end respectively and L^v is operator that defines mathematical model of the line.

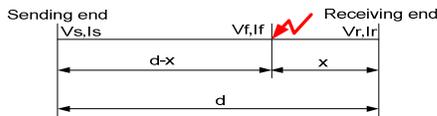


Fig. 4. Faulted transmission line

B. Implementation and usage of neural networks

In order to satisfy protective relaying requirements fault must be detected and classified in real-time, and the calculations have to be robust and reliable technique must be used. Using neural network (NN) algorithm for fault detection and classification as well as fault location (section determination) is one solution. Unlike the common algorithms NN usage enables independence from commonly varying parameters: type of fault, fault location, fault impedance, voltage levels etc. NNs are trained by individual examples to capture general, always complex and nonlinear, relationships among data.

Extracting system behavior from large data sets into concise representation can be completed by using NNs. This procedure is called clustering. The idea is to recognize patterns among given data and sort them into different clusters. All patterns

that belong to the same cluster should be as similar as possible; on the other hand patterns that belong to different clusters should be as different as possible [17]. In the case that we directly apply samples of voltages and currents measured from one end of line as input data, by matching corresponding patterns it is possible to classify input data into different clusters as Fig. 5 shows. Clustering of input data may be done by using self-organizing maps as special types of NNs. Procedure is described in detail in [18].

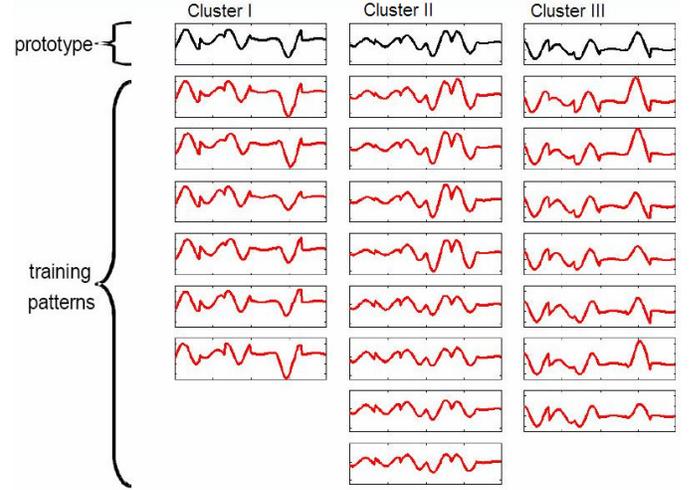


Fig. 5. Classifying clusters according to similar patterns [17]

In the case of protective relaying application there are different states of transmission line (Normal, AG, BG, CG, AB/ABG, BC/BCG, AC/ACG, ABC/ABCG, Zone I, Zone II etc.). After training, different clusters are established as Fig. 6 shows.

When new set of input signals is available, appropriate conditioning of input data is done in order to make them comparable with prototype cases. If the input pattern is in “normal-state”, data window is shifted for one sample and comparison is repeated again. In case that pattern belongs to faulted case, further classification is done. At the end, the state is classified as belonging to some of the existing clusters.

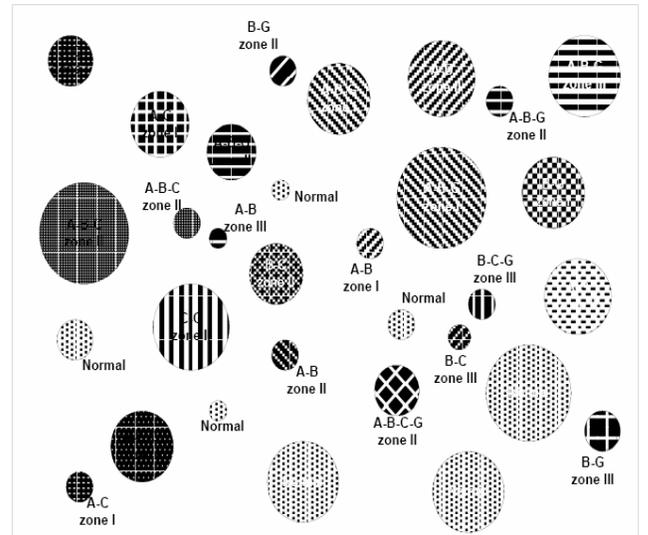


Fig. 6. Established data structures after training [13]

V. SYSTEM-WIDE SPARSE MEASUREMENT ALGORITHM

Although there are many accurate two-end and three-end algorithms [1-6], they are not always applicable because only data from limited number of substation are commonly available. In order to improve fault location when only limited recorded data are available, the “waveform matching” based method may be used [19].

A. Description of the Algorithm

If power grid status, as well as FL and fault resistance are known to the short circuit program, simulated waveform will completely match with recorded waveform for corresponding fault case. Waveform matching approach is based on the idea to compare recordings of faulted event against simulated recordings across the same power grid. By posing fault at different locations, different simulations are obtained. The simulation that matches the recorded fault event the best reveals FL. Value of (4) represents the matching degree of the comparison [19].

$$f_c(x, R_f) = \sum_{k=1}^{N_v} r_{kv} |V_{ks} - V_{kr}| + \sum_{k=1}^{N_i} r_{ki} |I_{ks} - I_{kr}| \quad (4)$$

Where,

$f_c(x, R_f)$ -the cost function using phasors for matching

x, R_f -the fault location and fault resistance

r_{kv}, r_{ki} -weights for the errors of the voltages and currents respectively

V_{ks}, V_{kr} -simulated and recorded during-fault voltages respectively

I_{ks}, I_{kr} -simulated and recorded during-fault currents respectively

N_s, N_r -the numbers of selected voltage and current phasors respectively

k -the index of voltage or current phasors

B. Implementation and use of the genetic algorithm

Accuracy of waveform matching method may be influenced by accuracy of performed simulation, as well as by the algorithm used for posing faults for next iteration of matching.

In automated FL procedure presented in section II power flow and short circuit study are performed by using PSS/E Short Circuit program as Fig. 2 shows [11]. In order to obtain system model that reflects status of the power grid new solution proposes use of EMS SCADA PI Historian. This tool is used for obtaining the load, branch and generator data from the time the fault occurred in order to update power system model before simulation is performed.

From (4) we notice that cost function will be zero if phasors obtained from simulated waveforms completely match phasors obtained from recordings. It is obvious that the best fault location is found as a global minimum of (4). Therefore FL estimation problem can be translated into optimization problem. An optimal way for posing faults based on genetic algorithm (GA) is used. Block diagram of this method is

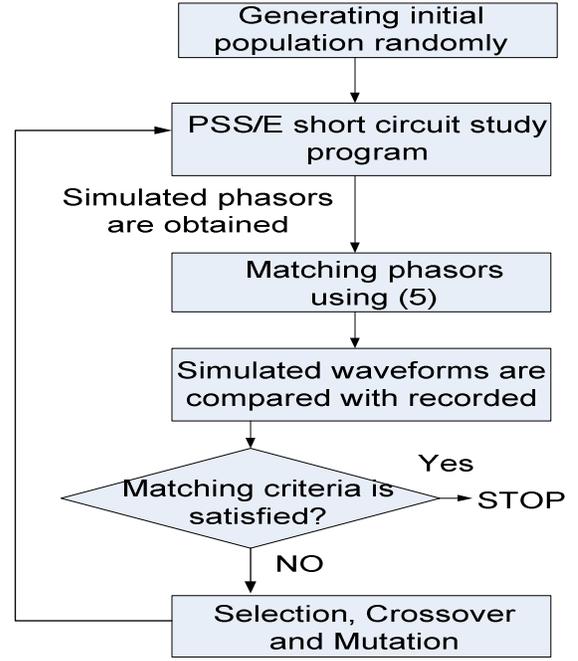


Fig. 7. Waveform matching block diagram

shown in Fig 7. In order to utilize GA, minimization problem is converted into maximization problem as shown in (5).

$$f(x, R_f) = C_{\max} - f_c(x, R_f) \quad (5)$$

Where,

$f(x, R_f)$ is the fitness function,

C_{\max} is the maximal fitness value in the current population

From (5) we see that x and R_f are selected as two variables, represented as binary strings in GA. Successive ‘generations’ of the population are created by several simple ‘genetic’ operators, as illustrated in Figure 8.

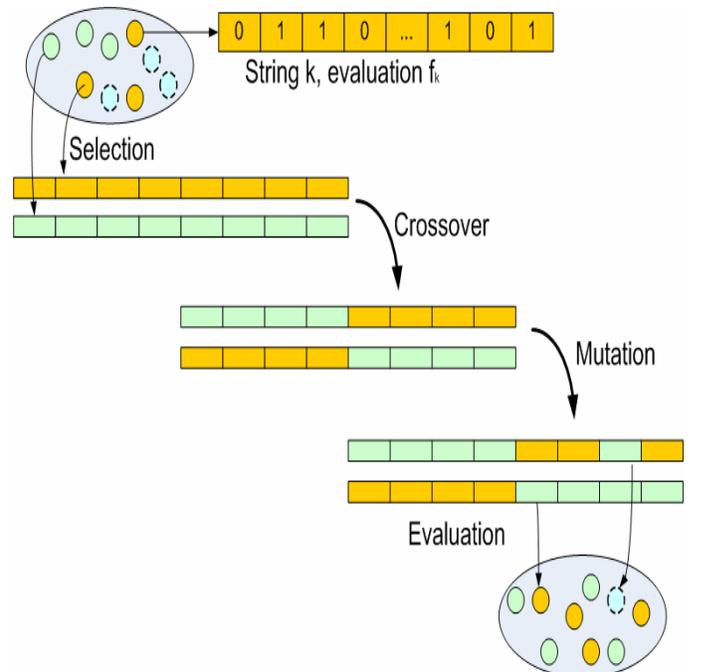


Fig. 8. A generation of simple genetic algorithm

By using three GA operators optimal fault posing for next iteration of matching is implemented [19]:

- a) Selection operator mimics the process of natural selection where the fittest members reproduce most often.
- b) Crossover operator, applied with probability, acts on a pair of selected members providing the exchange of binary strings.
- c) Mutation operator, applied with probability, affects the single bit in a member.

VI. CONCLUSION

This paper presents architecture of a procedure for optimal selection of FL algorithms that utilize different data sources. This approach has modular structure, which can be extended with new techniques as they become available.

Several FL algorithms and use of intelligent techniques are presented. First, need for local processing of single recording is explained and usage of expert system is presented. Then, synchronized sampling two-end algorithm is described and NN technique implementation used to enhance this algorithm is shown. Then use of genetic based algorithm for system-wide sparse measurement algorithm is explained. This is one of rare algorithms capable of estimating FL out of sparse measurements. It is based on waveform matching principle and capable of updating power grid status through EMS SCADA PI Historian. With the ability to update system model in real time this algorithm is drastically enhanced. With presence of parallel processors this algorithm could be further enhanced because greater number of possible faults could be placed and simulated for the same amount of time.

Besides applying the most suitable algorithm on available recordings that correspond to the same fault event, the approach presented in this paper speeds up centralized FL procedure. It presents example of applications and improvements that can be achieved by using different intelligent techniques and available IED data.

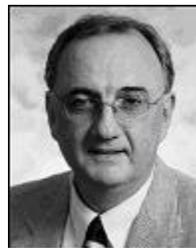
VII. ACKNOWLEDGMENT

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VIII. REFERENCES

- [1] Takagi, T., Yamakoshi, Y., Yamaura, M., Kondow, R., Matsushima, T., "Development of a New Type Fault Locator Using the One-Terminal Voltage and Current Data", IEEE Trans. on Power App. and Sys., Vol. PAS-101, No. 8, Aug. 1982 pp 2892-2898.
- [2] M. Kezunovic, B. Perunicic, J. Mrkic, "An Accurate Fault Location Using Synchronized Sampling at Two Ends of a Transmission Line", 11th PSCC, Avignon, France, September 1993.
- [3] Novosel D., Hart D.G., Udren E., Garitty J., "Unsynchronized two-terminal fault location estimation", Power Delivery, IEEE Transactions on Volume 11, Issue 1, Jan. 1996, Page(s): 130 – 138
- [4] M. Kezunovic, Y. Liao, "Fault Location Estimation Based on Matching the Simulated and Recorded Waveforms Using Genetic Algorithms," Development in Power System Protection, Amsterdam, The Netherlands, April 2001.
- [5] M. Kezunovic, B. Perunicic, "Fault Location", *Wiley Encyclopedia of Electrical and Electronics Terminology*, Vol. 7, pp. 276-285, John Wiley, 1999
- [6] A. Johns, and S. Jamali, "Accurate fault location technique for power transmission lines," *IEE Proceedings*, vol. 137, pt. C, no. 6, pp. 395-402, Nov 1990.
- [7] M. Kezunovic, M. Knezev, "Temporal and Spatial Requirements for Optimized Fault Location," Hawaii Int'l. Conference on System Sciences, HICCS-39, Hawaii, January 2008.
- [8] M. Kezunovic, "Future Uses of Substation Data," *7th International Conference on Advances in Power System Control, Operation and Management - APSCOM 2006*, Hong Kong, October/November 2006.
- [9] Test Laboratories International, Inc.: "DFR Assistant - Software for Automated Analysis and Archival of DFR records with Integrated Fault Location Calculation", [Online]. Available: <http://www.tliinc.com>
- [10] IEEE Inc., 1999 "IEEE Standard Common Format for Transient Data Exchange(COMTRADE) for Power Systems", IEEE Std. C37.111-1999
- [11] PSS^TME Load Flow ©Siemens Power Transmission & Distribution, Inc., PTI, Schenectady, NY, USA
- [12] M. Kezunovic, Z. Ren, G. Latisko, D.R. Sevcik, J. Lucey, W. Cook, and E. Koch, "Automated monitoring and analysis of circuit breaker operation," *IEEE Transactions on Power Delivery*, vol. 20, no. 3, pp. 1910-1918, Jul 2005.
- [13] M. Knezev, Z. Djekic, and M. Kezunovic, "Automated circuit breaker monitoring," *IEEE PES GM 2007*, Tampa, FL, Jun 2007, pp. 1-6.
- [14] M. Kezunovic, I. Rikalo, C.W. Fromen, D.R. Sevcik, S.M. McKenna, D.Hamai, W.M. Carpenter, and S.L. Goiffon "Automated fault analysis using intelligent techniques and synchronized sampling," in *Proceedings of the CIGRE General Session, Paris, France*, pp. 1-8, Sep 1998.
- [15] M. Kezunovic, "Automation of fault analysis using DFR data," in *Proceedings of the 60th American power Conference*, Chicago, IL, pp. 91-98, Apr 1998.
- [16] CLIPS-<http://www.ghg.net/clips/CLIPS.html>
- [17] M. Kezunovic, S. Vasilic, F. Gul-Bagriyanik, "Advanced Approaches for Detecting and Diagnosing Transients and Faults," *Med Power 2002*, Athens, Greece, November 2002.
- [18] S. Vasilic, M. Kezunovic, "An Improved Neural Network Algorithm for Classifying the Transmission Line Faults," *IEEE PES Winter Meeting*, New York, Jan. 2002.
- [19] M. Kezunovic, Y. Liao, "Fault Location Estimation Based on Matching the Simulated and Recorded Waveforms Using Genetic Algorithms," *Development in Power System Protection*, Amsterdam, The Netherlands, April 2001.

IX. BIOGRAPHIES



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