

Implementing an Advanced Simulation Tool for Comprehensive Fault Analysis

Nan Zhang, *Student Member, IEEE*, and Mladen Kezunovic, *Fellow, IEEE*

Abstract—Many large scale system blackouts involve relay misoperations. Traditional relay algorithms and settings need to be evaluated under a variety of fault and no-fault system-wide scenarios to better understand the causes for misoperations. New fault diagnosis algorithms also need to be developed to assure improved relaying performance and then evaluated under various scenarios. This paper introduces advanced fault analysis simulation software based on the interactive MATLAB and ATP simulation. The software consists of two major parts, power system simulation and relay algorithm evaluation. The former part can automatically generate thousands of system-wide events at one time and extract the transients for fault studies. The latter part includes the traditional distance relay model and two new advanced fault diagnosis algorithms. The structure of the software enables easy simulation setup for different power system models.

Keywords—modeling, simulation, protective relaying, fault analysis, alternative transients program, MATLAB.

I. INTRODUCTION

According to the historical records, many large scale system-wide blackouts involve relay misoperations [1].

Evaluation and improvement of existing relay algorithms and settings as well as investigation of new techniques for relaying are very important for understanding and mitigating relay misoperations. The most common approach used by many researchers for studying relay algorithm performance is using a simple two-machine system and limited fault scenarios. This method, although easy to implement, can not reflect the relay algorithm performance in the context of system-wide disturbances. A software simulation tool for comprehensive study of different relaying and fault analysis algorithms under a variety of system-wide disturbances is needed.

In this paper, such a software simulation tool is introduced. The software package is developed using two commonly used simulation tools, MATLAB [2] and Alternative Transients Program (ATP) [3]. The simulation tool consists of two major parts: power system simulation and relay algorithm evaluation.

In the power system simulation part, two complex power system models, one from a section of an actual system and another from the WECC 9-bus system, are used for generating

fault and no-fault scenarios either deterministically or randomly. Alternative Transients Program (ATP) is used for setting the template system models and executing the simulation because of its higher speed. MATLAB is used as a control and interface tool for automatically finding the system component and setting the parameters for each simulation scenario. The measurements of voltage and current for each scenario are arranged and saved for analysis of relay algorithms. The structure of the software is model-independent and only minor modification is needed when it is applied to other power system models.

In the relay algorithm evaluation part, different relay algorithms can be implemented in MATLAB and evaluated using data from the power system simulations. Traditional distance relay algorithm, which is based on phasor computation and *mho* or *quadrilateral* characteristics settings, is modeled in this software. Two novel techniques, fuzzy ART neural network based fault detection and classification (NNFDC) algorithm as well as synchronized sampling based fault location (SSFL) algorithm, are also implemented. The evaluation procedure is the same for those algorithms and it can be also applied to study new techniques.

In Section II, the overall framework of the simulation software is introduced. The details about the power system simulation and relay algorithm evaluation are given in Section III and Section IV respectively. Section V demonstrates some simulation examples. Conclusions and references are given at the end.

II. OVERVIEW OF THE SIMULATION SOFTWARE FRAMEWORK

The overall framework of the developed simulation software package is shown in Fig. 1. The software has an interactive structure by using MATLAB and ATP. MATLAB is a widely used general purpose modeling and simulation tool and ATP is free software that can be used to implement accurate and fast electromagnetic transient simulation. The combination of these two simulation tools can benefit from advantages of both. Other similar approaches to connect the electromagnetic transient programs with MATLAB were described in recent years [4-6].

As mentioned earlier, the entire software consists of two parts: power system simulation and relay algorithm evaluation. In the power system simulation part, the power system model of interest is built in ATPdraw and a template *.atp* file without any events is then generated. The system components and their parameters are set in MATLAB. The user defines

This work is supported by NSF I/UCRC called Power Systems Engineering Research Center (PSerc), project titled "Detection, Prevention and Mitigation of Cascading Events", and in part by Texas A&M University.

N. Zhang and M. Kezunovic are with the Department of Electrical Engineering, Texas A&M University, College Station, TX 77843-3128, USA (e-mails: zhangnan@ee.tamu.edu, kezunov@ee.tamu.edu)

disturbance scenarios through the interface in MATLAB. For each scenario, the MATLAB program will load the template .atp file and create a temporary file by modifying the settings of the template .atp file. After the ATP is executed, the transient measurements for each scenario are then stored for evaluation of relays or other fault analysis algorithms.

In the relay algorithm evaluation part, the raw data obtained from the measurements are then preprocessed according to the algorithm requirements. The processed data is analyzed by different relay algorithms and the analysis results are recorded and compared under the actual features of the scenarios.

When applied for different system models, the software only needs to rebuild the ATP template model and update the system configuration settings in MATLAB. The other parts need not to be changed. The reason is given in the next section.

III. POWER SYSTEM SIMULATION

A. Power System Models

Two system models are implemented for comprehensive fault studies. Power system model #1 represents a real 345kV system section from CenterPoint Energy [7], as shown in Fig.2. The system has a specific topology and actual line parameters. It is suitable for generating a series of fault scenarios under different system conditions.

Power system model #2 is the WECC 9-bus system, as shown in Fig. 3, which is usually used in power flow studies and transient stability studies. Unlike system #1, which is too “strong” by having too many ideal sources, the 9-bus system

represents a common topology and is suitable for studying the influence of system-wide disturbances. Since the generator data is also available, the system is set up as a “dynamic” model using the embedded synchronized machine component SM59 in ATP. The dynamic scenarios such as power swing and out-of-step condition can be simulated as a result. The original lumped line parameters are modified to represent the distributed parameters.

Assuming the relay is installed at the “local end” labeled in both Fig. 2 and Fig. 3, the fault and some no-fault scenarios can be generated in these two power system models as listed in Table I and Table II in the Appendix.

The ATP model for power system #2 is shown in Fig. 4. To enable a model-independent software structure, the following rules should be followed in the system setup phase:

- i) In ATPdraw model setup, all the components representing line faults, switches, and measurements on the transmission lines of interest, should be preserved, as shown in Fig.4. The name of each node should be easily identifiable. Numbers are preferred when naming the nodes, and all the components in a line section should refer to the same numbers as their two bus nodes. This helps to easily locate the system component in MATLAB program.
- ii) In MATLAB model setup, a component list file *system_parameters.m* should be generated to identify the system components and configure their parameters.

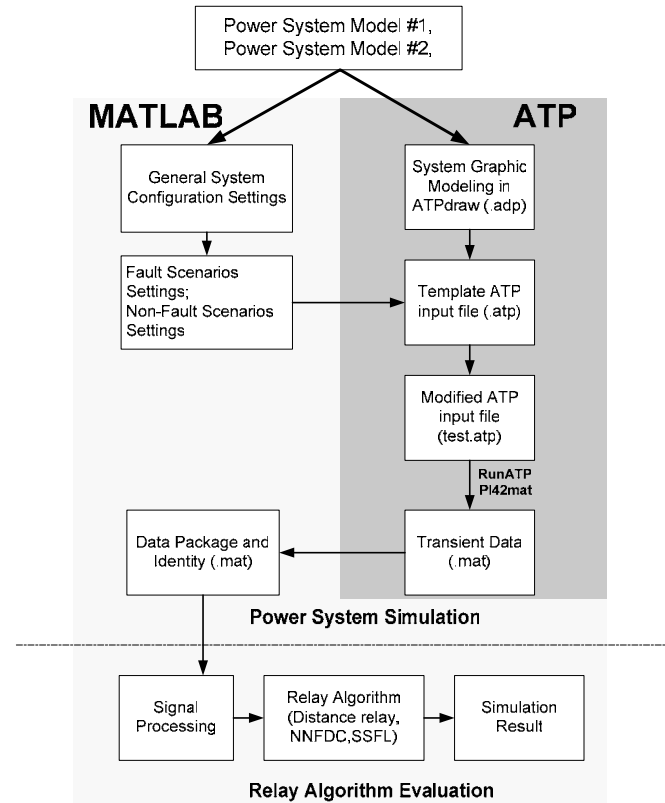


Fig. 1. The framework of the developed software package

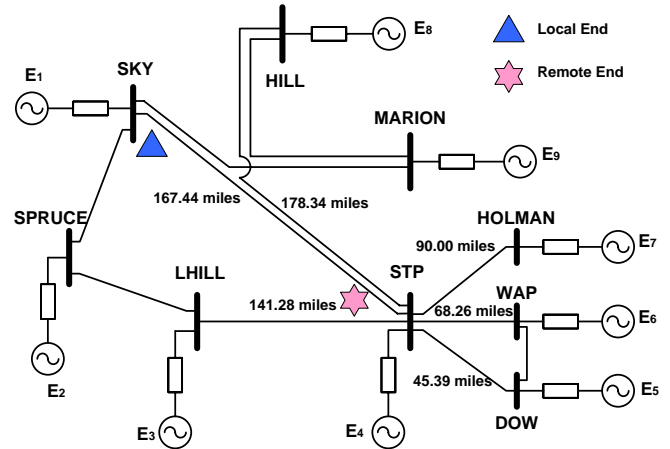


Fig. 2. Power System Model #1: Centerpoint SKY-STP system

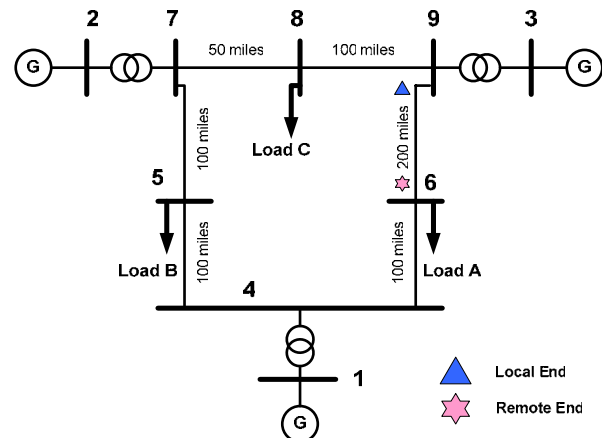


Fig. 3. Power System Model #2: WECC 9-bus System

using full cycle Fourier Transform. For NNFDC, the three-phase voltages and currents are normalized and arranged in a row to form a pattern. For SSFL, only raw samples in time domain are required.

- e) Fault Diagnosis. The pre-processed data is sent to the algorithm to implement fault detection, classification and location.
- f) Result Output. The results of fault diagnosis are compared with the scenarios to measure the analysis errors. The results are saved for further studies.

A. Distance Relay Modeling

Traditional distance relay algorithm can be found in several references, such as [8]. Using the computed phasors for three-phase voltages and currents, the apparent impedance of the relay is estimated for each of possible phase-to-phase (AB, BC, CA) and phase-to-ground fault types (AG, BG, CG). The impedances are then compared to the *mho* or *quadrilateral* characteristics [9], as shown in Fig.7. Selection of *mho* or *quadrilateral* characteristic depends on the value of zero sequence current. The existence of zero sequence current indicates ground fault and *quadrilateral* characteristic should be used. Otherwise, if the fault does not involve ground, *mho* characteristic should be used. When the operating characteristic is chosen, the impedance is examined against all three sets of individual settings. The type and location of an actual fault is concluded by checking whether the impedances fall within the zone settings. The timers of the zone settings are set as fixed values here.

The software model for distance relay, which is implemented in MATLAB, is an efficient way to evaluate relay performance using a large number of scenarios. The problems of relay setting or algorithm under certain conditions can be easily studied. The software models of relays, using different algorithms, are more or less a crude method that may not reflect the real situation. To confirm the accurate relay behavior under some specific conditions, the process can be replayed using actual physical relay device. This method can be found in [10].

B. Neural Network Based Fault Detection and Classification

A self-organized, ART neural network based fault detection and classification (NNFDC) algorithm is developed in [11]. The implementation of the algorithm in MATLAB is shown in Fig.8. Thousands of fault and no-fault scenarios from power system simulation are used for training the ART neural network, with the procedure shown in Fig. 9. After the iterated unsupervised and supervised learning, a set of prototypes will be constructed to represent each type of fault within each of preset zones, such as “AG fault in zone I”. Those prototypes for each fault are used by fuzzy K-nearest neighboring classifier for fault detection and classification of given test patterns.

The detailed algorithm and implementation of ART neural network based fault classification can be found in [11]. The improvement of the original algorithm to solve the application issues is proposed in [12].

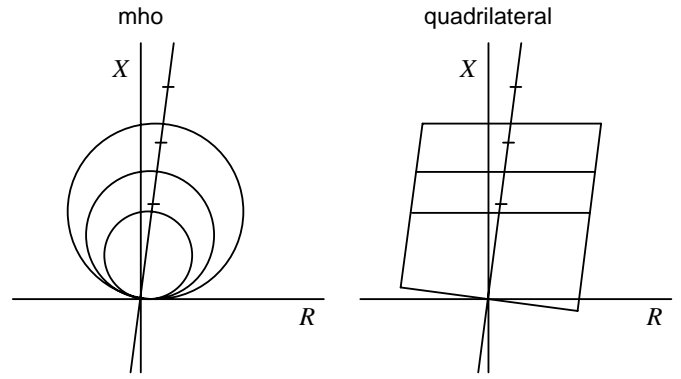


Fig. 7. *mho* and *quadrilateral* characteristics

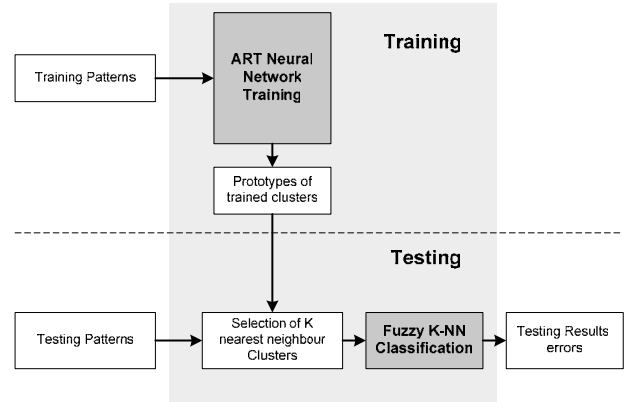


Fig. 8. Software Structure of NNFDC

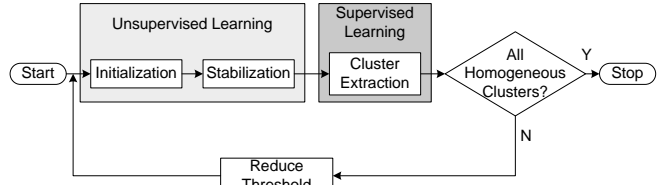


Fig. 9. Flowchart of neural network training

C. Synchronized Sampling Based Fault Location

Synchronized sampling based fault location algorithm (SSFL) is developed in [13]. The input of the algorithm requires time domain raw samples of voltage and current signals synchronously taken from both ends of the transmission line. Another input is the line parameters used in the line model. For short transmission line, the line is modeled using lumped RL parameters. The fault location is obtained directly using minimum square estimation method. For long transmission line, the line is modeled using distributed RLC parameters and the fault location is obtained indirectly using traveling wave method [13].

SSFL calculates the exact fault point of each fault type and compares it with the actual fault location. The error of SSFL is defined as:

$$Error(\%) = \frac{|Actual\ Location - Computed\ Location|}{Line\ Length} \times 100 \quad (1)$$

V. SIMULATION EXAMPLES

There are two methods to evaluate relay algorithms: static and dynamic tests. As shown in Fig. 10, the static test always takes the post fault values in a fixed data window (usually 1 cycle) to test the algorithms. The dynamic test takes the values throughout the entire event by a “sliding” data window. Usually, the static test is used for initial analysis and the dynamic test is used for detailed analysis of some specific events, such as power swing. Numerous simulations and evaluations of those algorithms are implemented in [11-14]. In this section, we just give two simulation examples for both types of tests.

A. Static tests in Power System #1

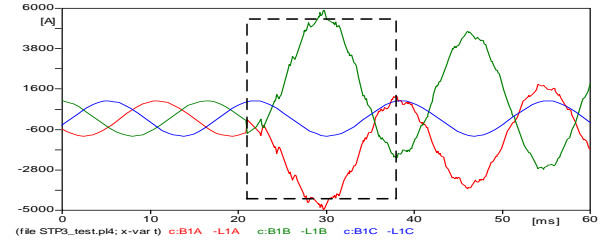
In this example, we use power system #1 to generate fault scenarios under off-nominal system conditions and evaluate performance of each relay algorithm. The relay algorithms are installed at SKY bus to protect SKY-STP line. There are two-zone settings for distance relay and NNFDC. Zone I reaches 80% of the primary line length and Zone II reaches 150% of the primary line length. In power system simulation, 500 fault scenarios are generated randomly on SKY-STP line under a system frequency of 59Hz. Fault parameters are randomly selected from all fault types, 0-100% fault locations, 0-30 Ω fault resistances, and 0-360° fault inception angles. The fault detection and classification error is recorded for distance relay and NNFDC. The average fault location error of those 500 cases is also recorded.

In this test, the errors are 20.80% for distance relay, 5.4% for NNFDC and 0.295% for SSFL. For distance relay and NNFDC, most of the false cases are from the faults occurring around the zone boundary. NNFDC performs much better than distance relay due to its constructed knowledge by learning thousands of difference scenarios. SSFL is not influenced by the frequency variation.

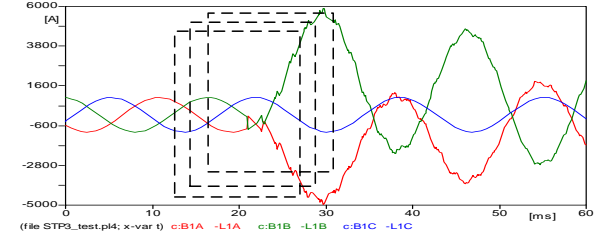
B. Dynamic tests in Power System #2

In this example, we use power system #2 to generate a power swing process. The relay algorithms are installed at bus 9 to protect line 9-6. There are three-zone settings for distance relay. Zone I reaches 80%, Zone II 150% and Zone III 250% of the primary line length respectively. Assume there is a three-phase fault occurring on line 4-5 at 0.01s (ABC fault, location 50%, resistance 11.1 Ω , inception angle 303.9°). The fault is cleared at 0.285s. After the fault is cleared, the system experiences a stable power swing. As shown in Fig. 11, the voltage and current for line 9-6 at bus 9 have the profile with an oscillation.

After the fault is cleared, distance relay sees the apparent impedance moving into its Zone III settings in three phase-to-phase *mho* characteristics, as shown in Fig. 12. Therefore it will conclude that there is another fault in Zone III and may trip the un-faulted line 9-6 if the timer expires. The conclusions of NNFDC and SSFL for this scenario both indicate that there is no fault either in the primary zone or backup zones. Therefore, no false trip will be initiated by those two algorithms.

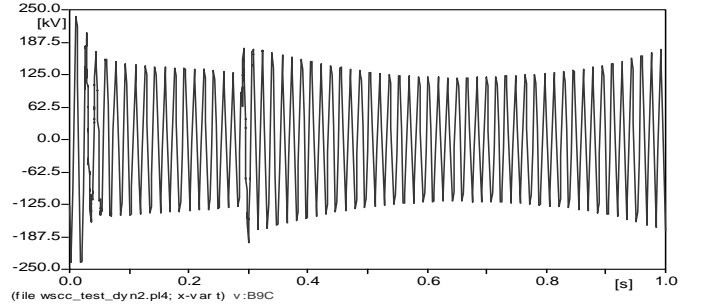


(a) Static test uses fixed data window for post-fault values

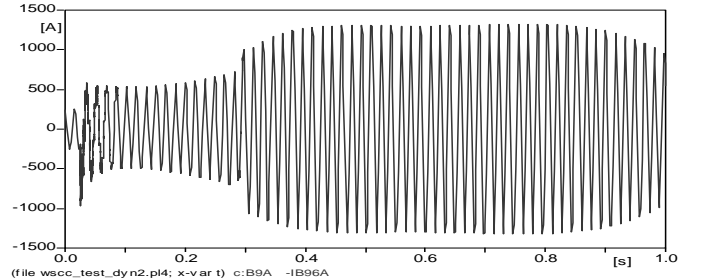


(a) Dynamic test uses sliding data window for entire event

Fig. 10. The structure of the data package



(a) Phase A voltage at bus 9 during the power swing



(b) Phase A current in line 9-6 during the power swing

Fig. 11. Oscillation of voltage and current at bus 9 and line 9-6

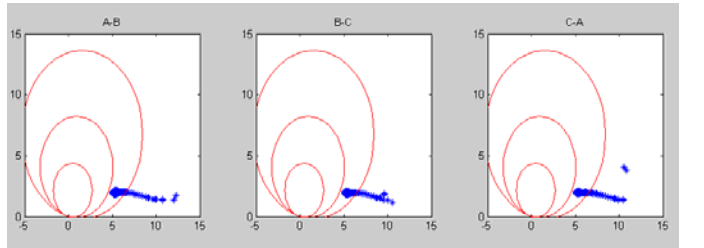


Fig. 12. Trajectory of impedance for distance relay of line 9-6 at bus 9 after fault clearing

VI. CONCLUSION

The context of system-wide disturbance analysis requires evaluation of traditional relay performance and development of new protection techniques. A handy software simulation tool is helpful for both studies.

The software package described in this paper can handle a variety of complex fault analysis under different system conditions. Thousands of scenarios can be simulated at one time. The structure of the software benefits from both programming flexibility of MATLAB and simulation efficiency of ATP. The software implementation makes it easy to change system models and evaluate other relay algorithms. New techniques for relay algorithm indeed have better performance than traditional relays in general. But they still need to be evaluated by a series of comprehensive studies.

VII. APPENDIX

TABLE I
FAULT SCENARIOS FOR BOTH OF POWER SYSTEMS

Type	Range
Fault type variation;	11 types + normal
Fault location variation;	0% - 100%
Fault impedance variation;	0 - $\infty \Omega$
Fault inception angle variation;	0 - 360°

TABLE II
SOME NO-FAULT SCENARIOS FOR POWER SYSTEM SIMULATION

System	Scenarios	Example
#1	Week infeed; Source voltage variation; System frequency variation; Load variation; Line switching;	E1 and E9 disconnected E1 voltage decrease by 5% All Sources with 59Hz E1 with -30° shift Disconnect any line
#2	Load variation; Line switching; Fault on other lines; Power Swings;	Switching on/off some load Disconnect any line Fault on any line Fault on 4-5, delayed clearing

TABLE III
METHOD FOR ADJUSTING PARAMETERS IN ATP

Parameter	Method
Fault type	Adjust opening/closing time of related phases of fault circuit switches
Fault inception time	
Fault location	Depends on line model, either adjust the line section resistance and reactance or just adjust the length of each section.
Fault impedance	Adjust impedance from fault point to ground
Line switching	Adjust opening/closing time of the switch
Source/load variation	Adjust voltage amplitude, phase angle, and impedance
Frequency variation	Adjust all source frequencies
Simulation time step, entire simulation time	Adjust general settings

VIII. REFERENCES

- [1] NERC Disturbance Reports, North American Electric Reliability Council, New Jersey, 1996-2001.
- [2] The MathWorks, Inc.: "Using MATLAB"; (Natick, Massachusetts, January, 1999).

- [3] CanAm EMTF User Group, *Alternative Transient Program (ATP) Rule Book*, Portland, 1992.
- [4] M. Kezunovic, Q. Chen, "A novel approach for interactive protection system simulation", *IEEE Trans. on Power Delivery*, Vol.12, No.2, April 1997.
- [5] J. Mahseredjian, F. Alvarado, "Creating an electromagnetic transient program in MATLAB: MatEMTP", *IEEE Trans. on Power Delivery*, Vol.12, No.1, Jan. 1997.
- [6] J. Mahseredjian, G. Benmouyal, et al., "A link between EMTF and MATLAB for user-defined modeling", *IEEE Trans. on Power Delivery*, Vol.13, No.2, April 1998.
- [7] D. Ristanovic, S. Vasilic, M. Kezunovic, "Design and implementation of scenarios for evaluating and testing distance relays," North American Power Symposium - NAPS, College Station, Texas, Oct. 2001.
- [8] W. A. Lewis and S. Tippet, "Fundamental basis for distance relaying on 3-phase systems," *AIEE Trans.*, vol. 66, pp. 694-708, Feb. 1947.
- [9] SEL-321 Phase and Ground Distance Relay, Directional Overcurrent Relay, Fault Locator: Instruction Manual, Schweitzer Engineering Laboratories Inc., Pullman, WA, Mar. 1998.
- [10] M. Kezunovic, Y.Q. Xia, et al., "Distance Relay Application Testing Using a Digital Simulator," *IEEE Transactions on Power Delivery*, Vol. 12, No. 1, pp. 72-82, January 1997.
- [11] S. Vasilic, M. Kezunovic, "Fuzzy ART neural network algorithm for classifying the power system faults," *IEEE Trans. on Power Delivery*, vol. 20, no. 2, pp.1306-1314, April 2005.
- [12] Nan Zhang, M. Kezunovic, "Coordinating fuzzy ART neural networks to improve transmission line fault detection and classification," IEEE PES General Meeting, San Francisco, June 2005.
- [13] M. Kezunovic, B. Perunicic, and J. Mrkic, "An Accurate Fault Location Algorithm Using Synchronized Sampling," *Electric Power Systems Research Journal*, Vol. 29, No. 3, pp. 161-169, May 1994.
- [14] Nan Zhang, M. Kezunovic, "A study of synchronized sampling based fault location algorithm performance under power swing and out-of-step condition," St. Petersburg PowerTech' 05, St. Petersburg, Russia, June 2005

IX. BIOGRAPHIES



Nan Zhang (S'04) received his B.S. and M.S. degrees from Tsinghua University, Beijing, China both in electrical engineering, in 1999 and 2002 respectively. Since Jun. 2002, he has been with Texas A&M University pursuing his Ph.D. degree. His research interests are power system analysis, power system protection, power system stability, system-wide disturbances, as well as signal processing and artificial intelligence applications in power systems.



Mladen Kezunovic (S'77, M'80, SM'85, F'99) received his Dipl. Ing. Degree from the University of Sarajevo, the M.S. and Ph.D. degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively. Dr. Kezunovic's 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 the Eugene E. Webb Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for equipment evaluation and testing as well as application of intelligent methods to control, protection and power quality monitoring. Dr. Kezunovic is a registered professional engineer in Texas, and a Fellow of the IEEE.