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Optimized Fault Location

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A continuous and reliable electrical energy supply is the objective of any power system operation. However, faults inevitably occur in power system due to bad whether conditions, equipment damage, equipment failure, environment changes, human or animal interference and many other reasons. Since it is very important that correct information about fault location and its nature is provided as fast as possible, an automated system is proposed to track status of equipment and to calculate fault location. Calculated results are available to users through detailed graphical representation. This paper presents elements of proposed solution and describes the benefits.

Introduction

When fault occurs in power system protection relays will trip circuit breakers (CBs), which will de-energize faulted line. Different devices will record corresponding current, voltage and status signals. This data is later used by different utility staff responsible for fault investigation. Changes in the equipment status will immediately be seen in the control center by the operator who will make a record of the fault event in and inform others like protection group and/or maintenance. Depending on the tools the person retrieving data from monitoring devices has on his/her disposal, the analysis process may last from few minutes to few hours. Frequently a lot of time may be spent by a person doing analysis waiting for others to provide some additional data.

To improve fault analysis and system restoration procedure, automated system that uses Visual Interactive Distributed (VID) spreadsheet is proposed. This solution is capable of automatically extracting data from different recording devices and utilizing it to evaluate equipment behavior using an expert system. It is also capable of calculating the fault location (FL) using optimized fault location algorithm (OFLA). Once data are processed, corresponding results are simultaneously shown to different utility staff using VID spreadsheet. The VID spreadsheet enables users not only to have an accurate determination of the FL but also to have graphical view of physical transmission line environment in vicinity of FL through a satellite image, to monitor how CBs behaved using 3D graphics, and to view construction details of towers and parameters of transmission lines using models as needed. Most importantly, all the information is made available to the users automatically.

The paper starts with discussion of FL application features in the existing framework used for fault analysis. After that new approach is presented. First, software architecture and its components consisting of data retrieval, FL and VID spreadsheet modules are presented. This is followed by more detail description of each module. Finally, benefits of the new approach are emphasized in the conclusion.

Characteristics of Existing Approach

The time line shown in Figure 1 demonstrates actions of utility personnel in the existing fault investigation approach. There are few features of the existing approach that are further evaluated: data availability, response time and decision quality, and personnel productivity.

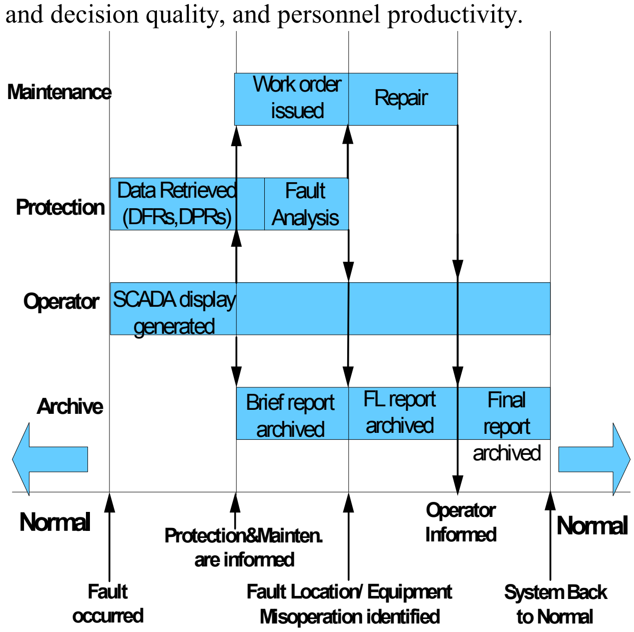

Figure 1: Timeline of utility personnel actions in case of permanent fault

1) Data availability
When fault occurs, different data and information are available to different utility groups. Operators have access to SCADA data all the time. Protection group retrieves

fault recordings from intelligent electronic devices (IEDs) located in substations in order to do fault analysis. Protection group does not have SCADA information readily available. Maintenance group is informed by the operator that a permanent fault is present, but they take action once they get FL estimation from the protection group. Maintenance group typically does not have access to other on-line data sources beside the archived data prepared by the operators and protection staff.

2) Response time and decision quality

Depending on correctness and readiness of available data and information created by different utility groups, fault can be cleared in varying time intervals. For operator it is very important to have a response from other groups about fault event as fast as possible in order to know when faulted line can be restored. Actions of other groups may have to be delayed until protection staff gets the required data and makes conclusions about FL. If estimated FL is not correct maintenance crew will take longer to patrol the line until they find the fault through visual inspection.

3) Personnel productivity

Use of different data by different utility groups leads to a lot of wait time by each group because the groups depend on each other when making final decisions. Particularly, the protection group needs to spend a lot of time retrieving the relevant data. In case that there are more fault events occurring as a result of a bad storm, protection group may be burdened by manual analysis of multiple events. Maintenance crew, although alarmed when fault is present, is not capable of knowing where exactly to go before protection group identifies FL. As a result, the productivity of each group is affected due to the mentioned manual process of retrieving the data and exchanging information.

New Approach

With technological advancements, measurements taken from different locations can be synchronized. IEDs are capable of communicating data to a central location. Data storage can easily be interfaced from different access points and intelligent techniques can be used for fast fault analysis. These benefits could be used to enhance existing fault investigation process. Shortcomings listed in the previous section can be improved by

- Speeding up FL analysis procedure through automation
- Applying the most suitable algorithm on the available recordings
- Visualizing the FL and operation of the involved equipment through different graphical means.

Figure 2 presents software architecture of the proposed solution. The architecture can be divided into three modules: a) Data retrieval, b) Optimal fault location and c) VID spreadsheet. They will be discussed in more details in the following sections.

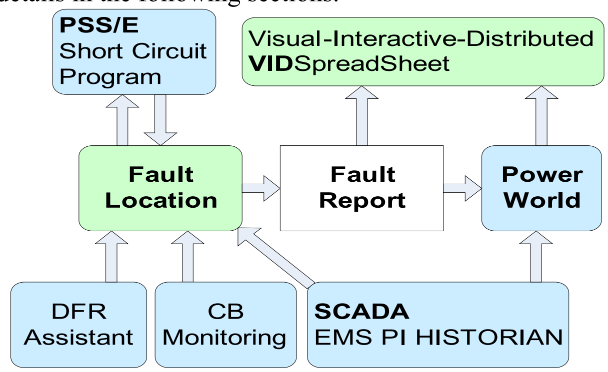

Figure 2: Software architecture

Data Retrieval Module

In order to calculate FL, two types of data may be needed: event data and power grid topology and status data. To automatically retrieve the data and extract related information, three software packages are used in proposed solution: DFR Assistant [1], Circuit Breaker Monitoring (CBM) Analysis [2] and SCADA PI Historian. The functions of the software packages used in proposed application are as follows:

a) DFR Assistant [1] automatically retrieves new event recordings from central repository (in COMTRADE format [3]) and preliminary expert system fault report. Report describes behavior of protection equipment and recognizes type of fault, which is used by other algorithms as input file.
b) CBM application [2] automatically retrieves recordings of CB operation from central repository (in COMTRADE format [3]) and an expert system report about CB operation. Report describes behavior of executed operation, final status of the equipment, and provides precise timings of event. This information may be used to align a group of switching actions that belong to the same event. This data is utilized to track the CB switching sequences and make conclusions about their performance and final outcome [4].
c) Custom designed software automatically retrieves SCADA PI Historian data. The data is used to update the system model (developed in PSS/E [5] format) before any calculation starts in order to reflect system state prior to a fault.

Fault Location Module

Once new data is obtained from DFRs, FL module is triggered automatically. It interfaces with a commercial PSS/E Short Circuit package [5] in order to run power flow and short circuit analysis automatically. As a result, it generates a fault report used by the VID spreadsheet. Architecture of this module is shown on Figure 3.

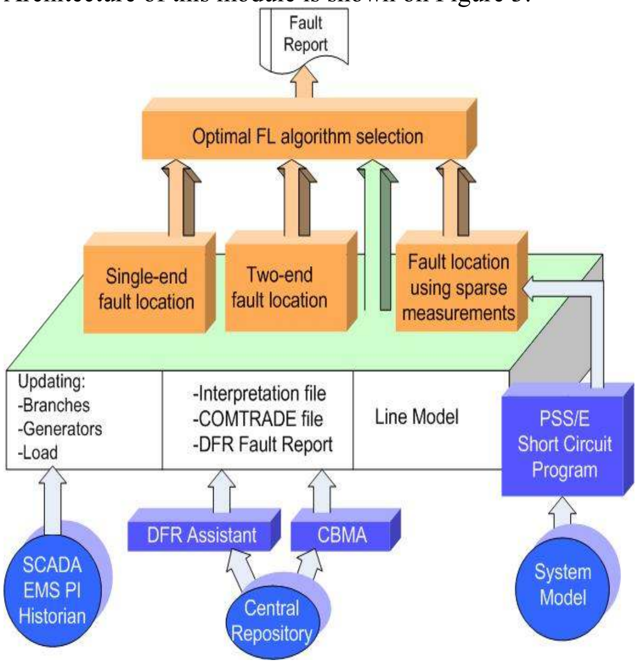

Figure 3: Architecture of fault location module

Beside samples from fault waveform recordings most FL algorithms need some additional data. In general, some FL algorithms are immune to fault resistance; some have accuracy that varies with transmission line length, and some depend on the use of short circuit programs. In [7] authors proposed an algorithm for selection of FL algorithm based on available information. They cover only two groups of FL techniques: a) algorithms based on phasors at one line terminal and b) algorithms that use voltages and currents from all line terminals. Neither the time-domain algorithms that use synchronized samples from two ends of the line, nor the most common case when only sparse recordings are available is covered in that algorithm. To calculate the FL most accurately, an automated procedure for selecting the best FL algorithm for a given circumstance is developed. The FL algorithms that are used as a possible selection include:
a) Synchronized sampling two-ended algorithm [8]
b) Unsynchronized sampling two-end algorithm [9]
c) System-wide sparse measurement algorithm [10]
d) Phasor-based single ended algorithm [11]
e) Single ended FL using symmetrical components [12]

In the case when data from two ends of faulted transmission line are available the two-end FL algorithm is the most accurate approach and should have priority. Otherwise it is checked whether data from only one end of the faulted line is available. In the case of the two-end algorithm, if input samples are synchronized, synchronized sampling two-ended algorithm is the most appropriate. Otherwise unsynchronized sampling two-ended algorithm is the most suitable. Similar logic is applied further and as conclusion OFLA shown on Figure 4 is developed.

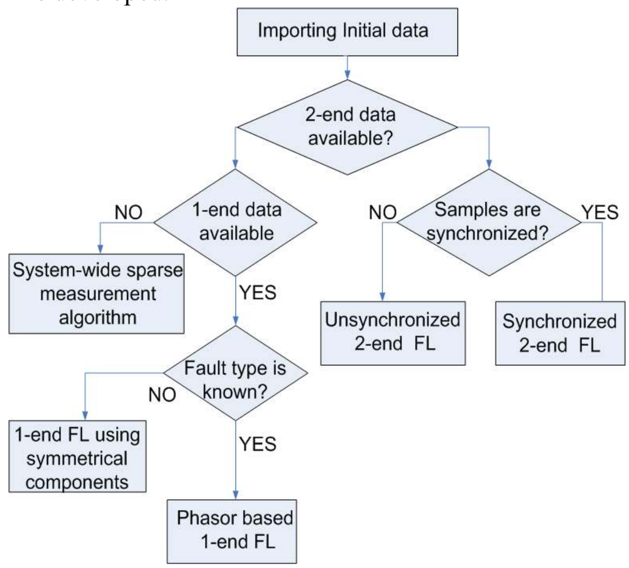

Figure 4: OPFL algorithm block diagram

It should be noticed that in some cases multiple algorithms are applicable and it would be interesting to check how averaging the results from different FL estimations using different weight functions for different algorithms could influence the final conclusion. In order to enable easy way for further testing and enhancing optimized FL algorithm, decision tree is used for implementing this algorithm.

VID Spread Sheet

Aim of the VID spread sheet is to provide the user with critical information through visualization. It should provide an easy way to access relevant information when system is in 1) normal state and 2) fault is present and system changes its state.

Architecture of visualization module is shown in Figure 5. It consists of two main blocks:
a) PowerWorld Retriever [6]. This is tool for real-time visualization of power system operations. Real time data are obtained from SCADA PI Historian. By default this tool is not capable of producing alarms when fault event is present in the system. So it was extended with two features:
  - Once new fault event is processed corresponding faulted line starts blinking.
  - Additional VID Spreadsheet button is added to interface. Once user clicks this button VID spreadsheet module is executed.

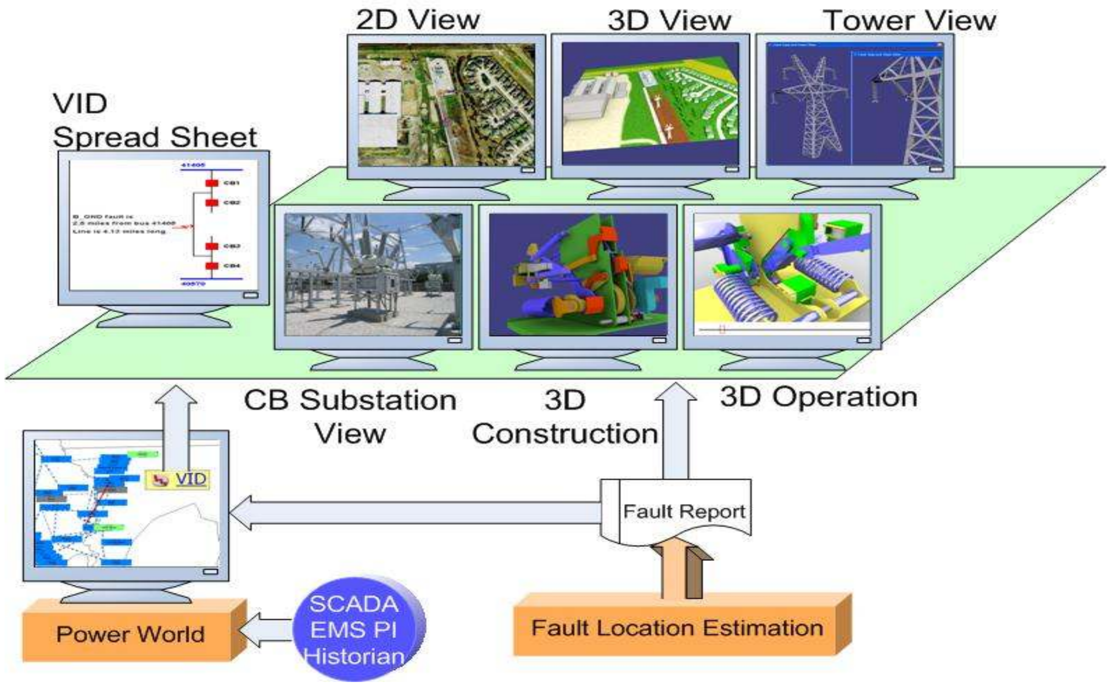

Figure 5: Visualization module architecture

b) VID spreadsheet. It provides user critical information about fault event through visualization. All input information that this module uses is provided through fault report by the FL module. Figure 6 summarizes views built in the VID Spreadsheet. Both, FL and equipment view will be demonstrated in following subsections.

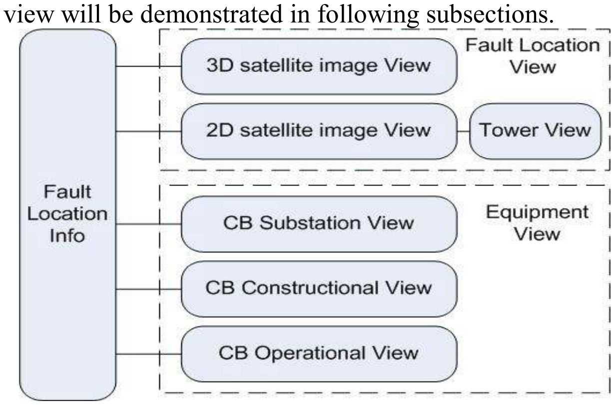

Figure 6: VID Spreadsheet architecture

Equipment View

Two types of equipment are modeled in the new approach:

- Tower
- Circuit Breaker

Tower is a complex structure that holds the transmission lines through insulators. If any fault occurs on particular segment of transmission line, it is likely that the fault occurs on the tower and insulators. The tower structure varies with voltage level and also depends on type of circuit it carries (either single circuit or double circuit). Based on the conductor arrangements, towers can be classified into single-level, two-level, three-level etc. Developed tower view is shown on Figure 7. It can be interactively rotated, enlarged, and reduced as needed.

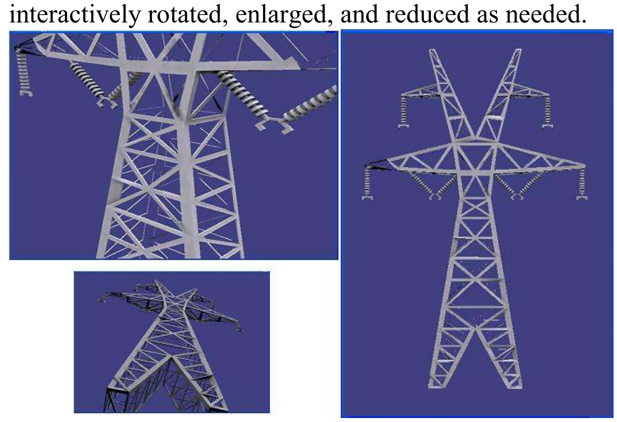

Figure 7: Constructional view of tower

Circuit breaker is electro mechanical device, which has several mechanical components such as, trip and close coils, trip and close latch mechanisms, connecting rod, rollers, cams etc. Visualization of these parts could help 'maintenance crew' to take better decisions for both diagnose and maintenance purposes. Visualization of CB is divided into two separate sections: constructional and operational view.

Constructional View is basically a 3D representation of the CB operating mechanism. A Westinghouse made vacuum circuit breaker of type 3 is used in developing the 3D representation. This particular breaker is equipped with spring operating mechanism (similar treatment can be applied to other types of operating mechanisms such as pneumatic and hydraulic). Constructional view of CB is shown on Figure 8. It is possible to rotate and change size of the object in all directions to give better understanding of constructional details.

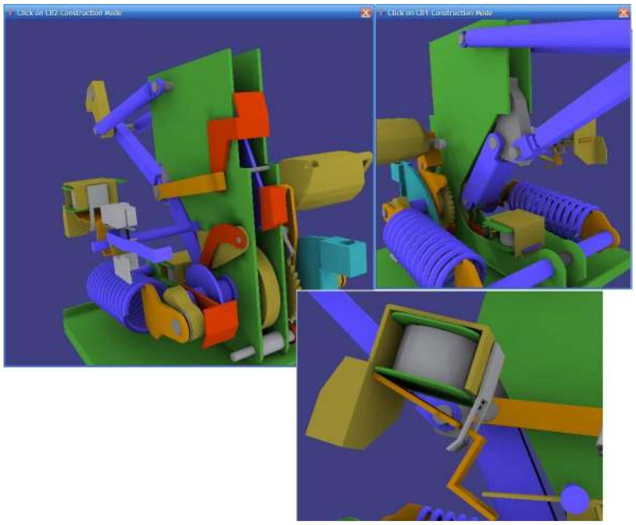

Figure 8: Constructional view of circuit breaker

With availability of recordings from CBM device, which records CB control circuit signals, each operation of CB is evaluated through an expert system analysis [2]. The idea of operational view is to show how the operating mechanism behaves during the operation of the CB. As the operating mechanism is often enclosed in a box, it is not easy to observe the movement of various parts. For selected CBM recording, corresponding signals were correlated with mechanical movements of CB. As a result operational view shown on Figure 9 was developed.

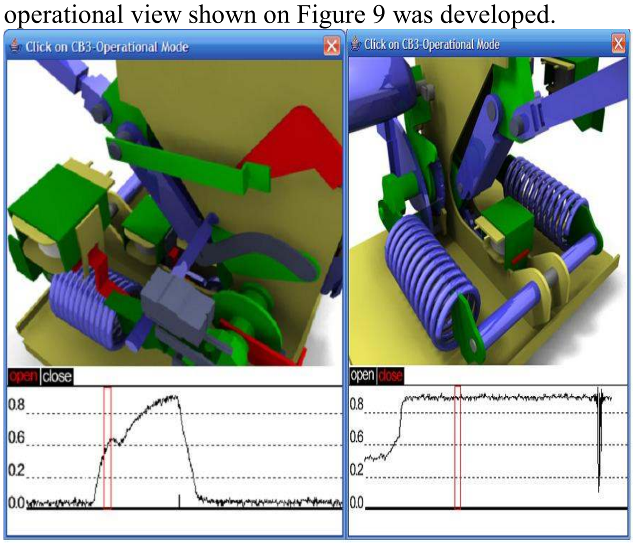

Figure 9: Operational view of opening and closing action of a circuit breaker

Fault Location View

This module translates results from FL file report into a view of the corresponding faulted area. Through this tool it is possible to see physical environment of the faulted area, as well as the behavior and status of equipment involved in the fault event. FL is shown through 2D and 3D view. It is possible to interact though these views by rotating them and zooming in and out. Examples of developed display are shown on Figures 10 and 11.

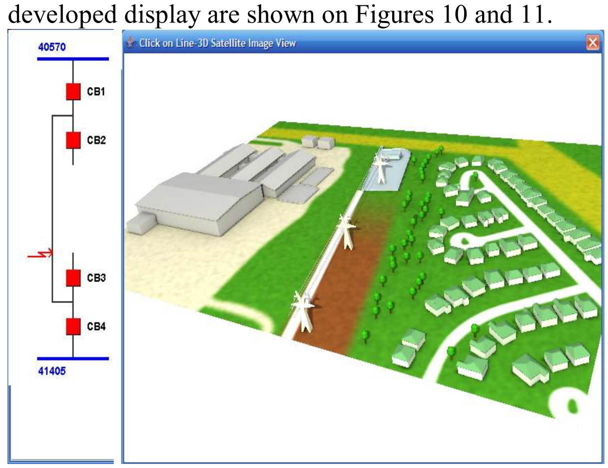

Figure 10: 3D view of fault location area

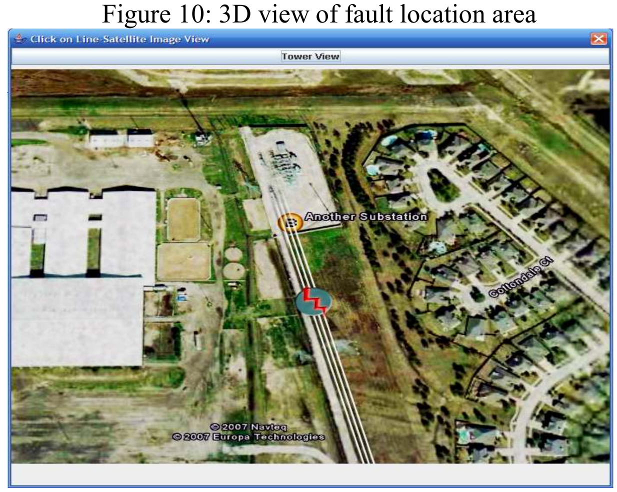

Figure 11: 2D view of fault location area

Conclusions

The following is a summary of the benefits achieved with this solution:

• System operators: Their main tool today is the SCADA system. Additional information used in the proposed approach is automatically obtained using additional data from substation IEDs. This will speed up the decision made by operator in restoring the system.

• Protection engineers: Instead of spending a lot of time on processing IED data manually, this group will be unburdened from the routine analysis tasks that will be performed automatically and will able to concentrate on complicated cases that require their involvement.

• Maintenance staff: Automatic analysis will immediately provide information about the fault location and this group will be able to immediately take some actions, instead of waiting for instructions from other groups. This will significantly reduce the time spent on fault repair and system restoration. At the same time CB maintaining is improved, because each CB operation is automatically analyzed and results are accessible through different views.

After analysis is done automatically there is no need for training any of the existing user groups.

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Biographies

Mladen Kezunovic (S'77-M'80-SM'85-F'99) received the Dipl. Ing, M.S. and Ph.D. degrees in electrical engineering in 1974, 1977 and 1980, respectively. Currently, he is the Eugene E. Webb Professor and Site Director of Power Engineering Research Center (PSerc), an NSF I/UCRC at Texas A&M University. He worked for Westinghouse Electric Corporation, Pittsburgh, PA, 1979-1980 and the Energoinvest Company, in Europe 1980-1986. He was a Visiting Associate Professor at Washington State University, Pullman, 1986-1987. He spent his sabbatical during 1999-2000 at EDF Research Center in Clamart. 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 has published over 350 papers, given close 100 seminars, invited lectures and short courses, and consulted for over 20 companies worldwide. He is the Principal of Test Laboratories International, a consulting firm specializing in automated fault analysis and test methods for substation IEDs. Dr. Kezunovic is a Fellow of the IEEE, a member of CIGRE and Registered Professional Engineer in Texas.

Ergun Akleman (M'00) received the B.S. in electronic and communication engineering in 1981 from Istanbul Technical University and M.S. and Ph.D. degrees in electrical and computer engineering, in 1986 and 1992, respectively from Georgia Institute of Technology. Currently, he is professor in Department of Architecture at Texas A&M University He worked as an assistant professor, in department of Computer Science at Yildiz Technical University 1992-1995. He was an adjunct assistant professor at Marmara and Bosphorous Universities, 1993-1995 and 1994-1995 respectively. He is also a professional cartoonist who has published more than 500 cartoons. In Texas A&M, his main affiliation is the Visualization Science program where he teaches a wide variety of topics in covering both artistic and scientific aspects of computer graphics. His research is also interdisciplinary, usually motivated by aesthetic concerns. He has published extensively in the areas of shape modeling, image synthesis, artistic depiction, image based lighting, texture and tiles, computer aided caricature and visual storytelling. His most significant and influential contributions have been in computer aided sculpting. His work on topological mesh modeling resulted a widely used manifold mesh modeling system, called TopMod.

Maja Knezev (S'03) received her Dipl. Ing. degree in electrical engineering from the University of Novi Sad, Serbia, in 2004. Since 2005 she has been a M.S. student in the Department of Electrical Engineering, Texas A&M University, College Station. Her research interests include fault location, power system monitoring, protective relaying and substation automation.

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Satish Natti (S'06) received the B.E degree from Andhra University, India, in 2001, and the M.Tech. degree from Indian Institute of Technology, Kanpur, India, in 2003. He is pursuing the Ph.D. degree in Electrical and Computer Engineering at Texas A&M University, College Station. His research interests are power system reliability, maintenance and asset management.