Automated Circuit Breaker Monitoring

Maja Knezev, Zarko Djekic, *Student Members, IEEE,* and Mladen Kezunovic, *Fellow, IEEE*

***Abstract*-- Circuit breakers are used in a power system to break or make current flow through power system apparatus. The action of circuit breakers changes switching topology of a power system. Reliable operation of circuit breakers is critical to the ability to reconfigure a power system and can be assured by regular inspection and maintenance. An automated circuit breaker monitoring system is proposed to monitor circuit breaker's control circuit. System is designed to enable deployment of system-wide applications that utilize the data recorded by the system. An application of system wide data analysis is demonstrated. It makes possible to track the circuit breaker switching sequences and make conclusions about their performance and final outcome. Lab and field evaluation of the designed system is performed and results are presented.**

Index Terms--circuit breakers, power system monitoring, power system maintenance, SCADA systems, substation measurements, topology.

I. INTRODUCTION

THE Circuit Breakers (CBs) are part of a power system and their functioning is critical to providing continuous power supply. They are used to configure a power system as needed, to control the load flow and disconnect any faulted parts of the system. Once installed, a breaker may have a lifetime of over 40 years. Its operating state changes very infrequently unless it is located in switching stations with intense switching schedule. A breaker has no intelligence of its own. It is operated by protective relays, which detect faults on the system and identify the appropriate CBs that need to be opened in order to isolate the faults and enable the system to function. Also, a breaker may be operated through a manual command issued either remotely by power system operators or locally by maintenance personnel. Some times the breaker may not open or close on command, leading to an interruption in the operator switching action leading to an incomplete control action or unsuccessful fault clearing allowing the fault to exist longer than the system can sustain without damage. Misoperation of CBs can result in undesired changes in system functioning that may cause the system to go into an abnormal state, potentially causing power outage. The CB represents a critical part of the protection system, as well as the Supervisory Control and Data Acquisition (SCADA) system.

This work was supported by DOE CERTS Project "Automated Circuit Breaker Monitoring". M. Kezunovic, M. Knezev and Z. Djekic are with the Department of Electrical Engineering, Texas A&M University, College Station, TX 77843-3128, USA (e-mails: mknezev@tamu.edu, djzare@tamu.edu, kezunov@ece.tamu.edu).

Different monitoring systems have been designed and proposed to monitor the status of CBs and predict optimal maintenance schedules based on the following measurements: the mechanism velocity, phase currents, gas pressure and temperature [1], vibration signals [2] etc. A report by CIGRE shows that approximately 25% of the major and minor failures of circuit breakers in service are caused by control circuit failures [3]. Some of the data acquisition systems currently available for measuring signals from the control circuit [4], [5], [6] are not suitable for on-line monitoring of breaker performance in a switching sequence that involves multiple breakers [4-6]. As a result they do not record enough information to make accurate diagnosis of the switching performance deterioration that may occur simultaneously on multiple breakers. Most of the monitors do not have sufficient number of channels, online recording and time synchronization capabilities to enable the artificial intelligence tools to make good decisions about the status of the breaker and/or system.

Data collected from circuit breakers in substations across the system may be combined to make deductions about the system switching state and performance that affect reliability. This application requires that the collected data be synchronized in time. Most of the existing monitoring systems do not have any option for time synchronization of recorded data. This limits application of data only to the usage for maintenance purposes on a single breaker. With thousands of breakers to be monitored these limitations serve as a deterrent to the adaptation of an online monitoring strategy on a large scale. While the circuit breaker monitor (CBM) data can provide information about the operation and status of individual breaker, substation and system-wide applications can help increase reliability by providing information about the sequence of events and topology of the power system. Some of this information is also obtained by SCADA. The redundant and more detailed information from circuit breaker monitors can be used to verify the consistency and increase redundancy of the measurements thereby increasing robustness of data and reducing operation errors. Using CBM data to improve power system operation and control are described in [7]-[8].

Architecture and functionality of the whole system is described in the first and second section of the paper. Third section explains the designed hardware and its role in the overall proposed system. The fourth section explains organization of analysis software of the CBM system. Lab and field evaluation of the CBM system is presented in the fifth section.

II. System Architecture

Architecture of the complete system can be divided into two parts: a) hardware, which includes Intelligent Electronic Devices (IEDs) and communication to the data repository PC and b) software, which performs automated analysis of field-recorded data related to operations of a group of breakers involved in the same switching action.

A. Hardware Architecture

Circuit Breaker Monitor (CBM) hardware consist of IEDs located at the circuit breaker cabinets in the switchyard, concentrator PC and GPS clock receiver located in a control house, and wireless point to multipoint network connecting IEDs located in the switchyard with the PC located in control house. This configuration works as the master-slave architecture; the slave CBM units are set up at each breaker in the switchyard and are hardwired to acquire the signals from CB's control circuit. The master unit (Concentrator PC) is set up at the control house to gather the data collected by all slave units in the substation, store and process it. The system is designed to allow configuration with multiple slave IEDs depending on the number of circuit breakers in a substation. Fig. 1 shows the hardware architecture of the CBM system in a substation.

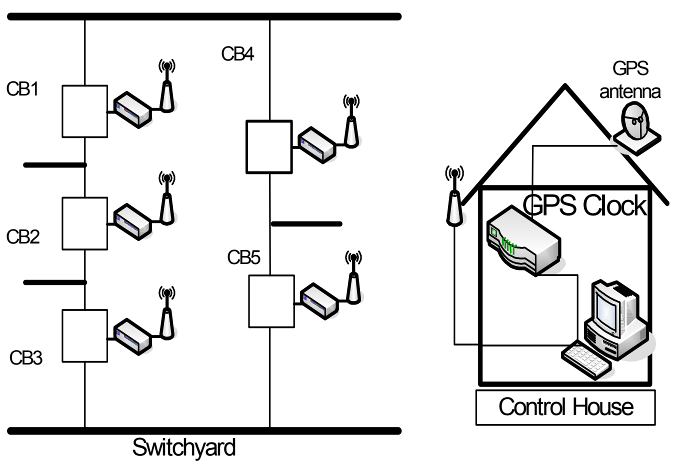

Figure 1: CBM Hardware architecture

When a breaker operates, CBM records control circuit waveforms and transmits recorded files to the concentrator PC using wireless communication. A list of signals recorded by a CBM and an example of recorded waveforms are given in Table I and Fig. 2 respectively.

From Table I, it may be observed that in order to monitor breaker operations closely, 15 signals are recorded including the phase currents through dedicated sensors wired inside the breaker. The obtained information is far more elaborate than what is acquired through breaker monitoring using typical wiring practice for remote terminal units (RTUs) of a SCADA system.

TABLE I
Circuit Breaker Control Circuit Signals

Signal Name	Analog(A)/ Status(S)	Nominal Range	Function
		VOLTAGES	
Control Voltage	A	125V± 15V	Provides Pos/Neg voltage for contacts
Light Wire	A	125V± 15V	ON/OFF Indicator
Aux. Contact B	A	125V± 15V	Establishes connection from Light to Neg
Yard DC	A	125V± 15V	Runs CB motor
Aux. Contact A	A	125V± 15V	Indicates breaker status
		CURRENTS	
Close Coil Current	A	< 10	Used to physically close the CB
Trip 1 Coil Current	A	<10A	Used to physically open the CB
Trip 2 Coil Current	A	<10A	Used to physically open the CB
Phase A Current	A	5A	Indicates breaker status
Phase B Current	A	5A	Indicates breaker status
Phase C Current	A	5A	Indicates breaker status
		EVENTS	
Close Initiate	S	125V± 15V	Initiates a close operation
Trip Initiate	S	125V± 15V	Initiates a trip operation
X Coil	S	125V± 15V	Closes all 52X contacts, Establishes a path from POS to 52CC
Y Coil	S	125V± 15V	Opens all 52Y contacts, Interrupts 52CC and X coil currents

From the enclosed waveform example in Fig. 2, it is obvious that a very close tracking of the changes in the signal behavior may be observed. This allows for close analysis of the causes of the changes and subsequently detailed conclusions may be reached both about a single breaker operation, as well as the sequence of breaker operations. This level of detail is not available today through a traditional SCADA system.

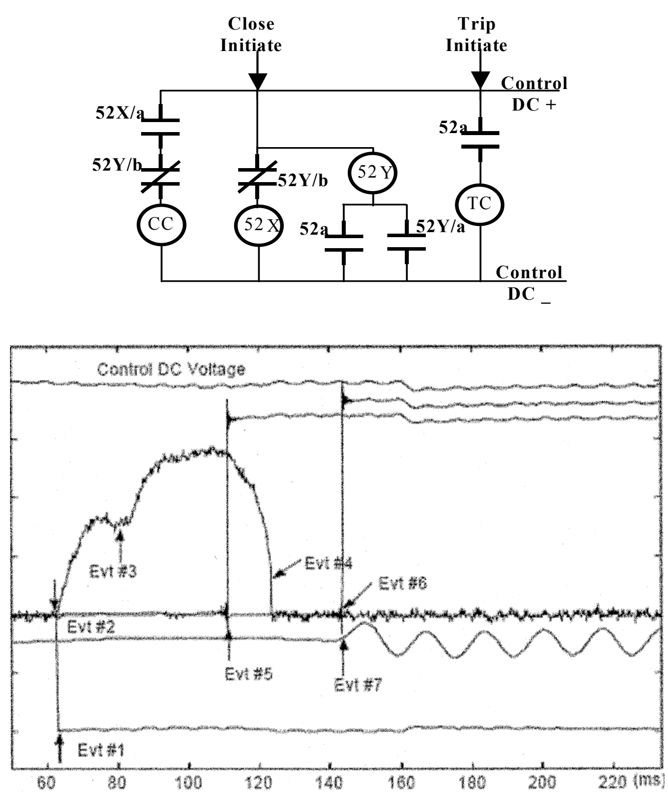

Figure 2: CB control circuit schematic and related waveforms

B. Software Architecture

Circuit Breaker Monitor software performs data analysis and outputs information for different users. Fig. 3 presents software architecture. The application enables customized views for various types of users since they may have different interest regarding breaker performance, sequences of breaker operations and network topology status. For some users it is important to know precise topology of the system and status of CBs in every moment and for some it is important to know precise sequence of operations of a group of CBs after fault was recognized and cleared.
Further details regarding software development are presented in section IV.

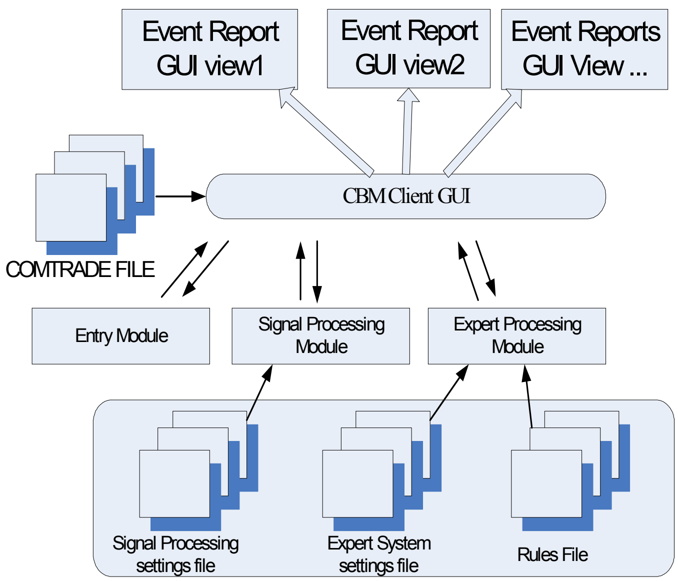

Figure 3: CBM Software architecture

III. Hardware

Two main functions that the circuit breaker monitoring (CBM) device is designed to perform are:

- Data acquisition: The input signals must be synchronously captured and converted to digital form when ever CBM is triggered.
- Transfer to central place: The data gathered by CBM units at breakers must be transferred to a central location for further processing and analysis.

The wireless transmission solution was found to be cost effective and easy to implement. If the data acquisition system were to be set up at each breaker in an entire substation, it would be very expensive to lay out the wires to connect the units to a control house in that substation. The CBM unit connected to a CB consists of 4 important components: signal conditioning, analog to digital conversion, processing and wireless transmission modules. Fig. 4 shows the block diagram of a slave unit.

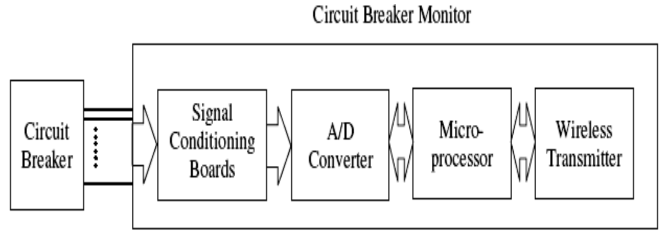

Figure 4: CBM Hardware architecture

A. Signal Conditioning Module

The input signals shown in Table I must be scaled appropriately before converting them into digital form for processing and storage. Most analog to digital converters require the input signals to be in the ±10V or ±5V range. A signal conditioning circuit must scale the signals to be in the range required by the A/D converter. This signal conditioning board should protect the rest of the device from high voltage transients generated during trip or close coil operation.

B. Analog to Digital Conversion Module

The analog signals must be converted to digital form with a resolution high enough to allow an accurate analysis. A resolution of 12-16 bits is sufficient for most applications. The sampling rate must be high enough to enable accurate reconstruction of signals needed for the analysis. Sampling rate of 10 kHz is sufficient for most applications. To make sure that the recorded data may be combined with data from other CBMs and other IEDs installed in a power system all signals must be sampled synchronously and then converted to digital form.

C. Time Synchronization

All CBM slave units are synchronized to GPS time and all recordings are accurately time-stamped [9]. Time synchronization is implemented using a GPS clock receiver and wireless transceivers for time distribution to IEDs located in a switchyard. The GPS synchronization signal (1PPS - pulse per second) is distributed from the master radio transceiver located in the control house to the CBM slave units at each breaker. In this way only one GPS receiver per substation is needed. Transceivers used for CBM have an option for 1PPS signal distribution from master modem to several slave units.

Time stamp transfer from GPS to CBMs has been implemented using a CBM communication protocol. This setup shown in Fig. 5 achieves time accuracy better than 10usec, which satisfies the requirements for this application.

The sampling signal “start” comes from the local timer, which is synchronized with 1PPS signal from the GPS. Local timer is used as the time reference for the sampling that takes place between two synchronization pulses sent by the GPS receiver. The local clock has a very small time drift between the two pulses so the sampling accuracy is not affected. For every sample, the processor creates a time stamp using the GPS time code received through the communication protocol and the actual time from the local timer.

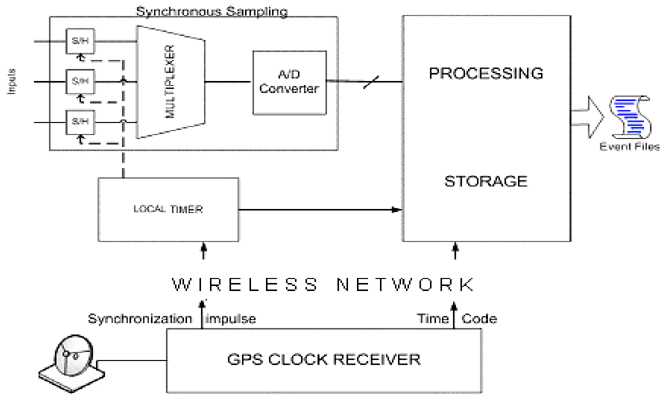

Figure 5: CBM Time synchronization circuit

Time stamp received from the concentrator determines the date, hour, minute and second. The microsecond resolution is determined by the local timer which is synchronized with GPS every second.

D. Microprocessor Module

Besides time synchronization, microprocessor module performs the following functions:

- Controls data acquisition parameters of the A/D converter
- Sets the signal sampling frequency and scaling factors for digital signals.
- Detects events and record data for specified duration in memory.
- Transmits data to concentrator PC using communication protocol and wireless transceivers.
- Receives and execute commands sent from concentrator

E. Wireless Communication Module

The Concentrator PC gathers data from all slave units through wireless communication. The wireless transmission system enables data transfer from multiple points to the central storage system. A wireless modem employing Frequency Hopping Spread Spectrum technology is used to transmit the collected data to the master unit in the control house. The transceivers work in a point-to-multipoint mode. In this mode, the slave units communicate with the master unit and vice versa but there is no communication between the slaves. In this mode the slave to master data link is usually robust, ensuring reliability of data transfer. The communication is controlled using custom point-to-multipoint protocol.

IV. Software

Three main functions that the CBM software analysis application is designed to perform are:

- Automated analysis of individual circuit breaker operation in real time
- Automated analysis of an operation of a group of circuit breakers
- Distribution of results though different GUI views and reports for variety of users

A. Automated Monitoring and Analysis

Availability of new data from CB's control circuit brings possibilities for new types of analysis. CBM device monitors signals from control circuit of CB as indicated earlier in Table I. The analysis application developed in an earlier project at TAMU analyzes performance and determines current status and behavior of an individual CB [10]. Detailed analysis of single circuit breaker behavior is of great importance for maintenance groups. Other utility groups like protection engineers are more interested in sequence of events associated with a group of circuit breakers. They are interested in knowing: when the sequence started, what caused operations, and finally whether the sequence executed correctly.

In order to meet the above requirements it was necessary to provide automatic retrieval of synchronized data from a group of circuit breakers to the central repository. This enabled new feature of comparing control circuit signals from different circuit breakers on the same time scale. CBM architecture is designed to uphold these features as Fig. 6 shows.

In the first iteration the analysis is done by the CBM Client software using local substation data. Later, locally extracted information from each substation is transferred to central repository. The CBM Server software at a central location analyzes behavior of a group of circuit breaker that may belong to different substations. Major benefit of locally extracted information is that the central office and communication channels are less burdened.

B. Topology and Sequence of Events Analysis

As mentioned earlier, automated analysis of CBM data has more information available to estimate CB status than what is available through existing tools. Since CBs track the topology change (connectivity of various components in power system) with more details, better information about the topology is available. Knowledge about the current state of the system

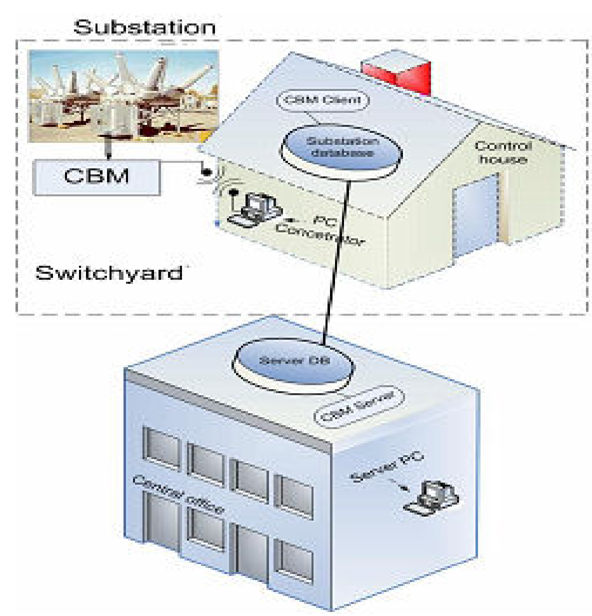

Figure 6: CBM system architecture

topology is very important for many power system applications like state estimation, fault location and alarm processor, which demonstrates the importance of the proposed architecture for future improvement of existing tools.

In general, CBs have the purpose to automatically connect or disconnect different parts of the power system in order to isolate the faults and/or re-route the power flow. In most cases they operate as a group in order to switch on/off some power system parts. To demonstrate this behavior we will consider small part of the network shown in Fig. 7.

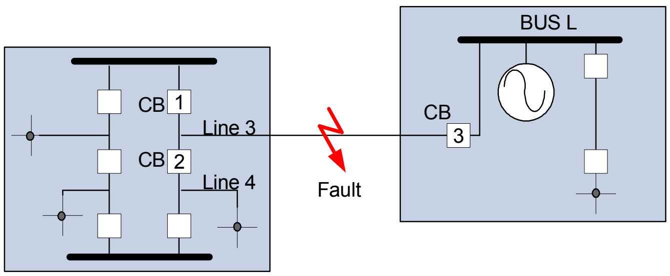

Figure 7: Example of fault present on transmission line

In case that fault is present on Line 3, corresponding breakers CB1, CB2 and CB3 shown in Fig. 7 should open and deenergize faulted line. After some time they will be re-closed automatically in order to check whether the fault is cleared [11]. Process of reclosing can be repeated a couple of times and it is initiated in order to determine whether fault, which caused opening of breaker, is still present. Sequence of events in case of a temporary fault present on Line 3 seen from the left hand substation from Fig. 7 is shown on Fig. 8.

It can be easily concluded that by monitoring the CBs status changes and recognizing operational bay groups of CBs using synchronized data, one can infer what was the reason for initiation of the sequence and was it executed as expected. Detailed analyzes of possible sequence of events for the case of breaker-and-a-half bus arrangement was performed using an automated software developed for this purpose.

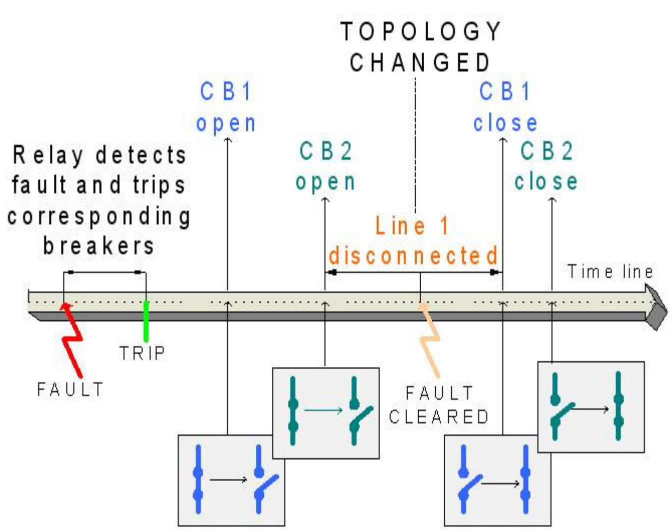

Figure 8: Sequence of events on CBs when fault is present

V. IMPLEMENTATION AND EVALUATION

Two Circuit Breaker Monitor units are designed, implemented and evaluated using:

- Laboratory tests
- Field tests

Laboratory tests involved individual module testing and integrated system testing. The signal conditioning boards were tested for both high-voltage and low-voltage signals. The A/D conversion module was tested with different types of signals: sinusoids, square waves, DC and scaled trip reference signals. The accuracy of conversion was tested and appropriate scaling factor was determined. The microprocessor module and the associated software were tested by repeatedly triggering the recordings using artificial trip signals. The wireless system was tested in a lab environment with 300 meters distance between the two units. The complete system was also evaluated in the laboratory using signals previously recorded in the field. A digital simulator was used to replay the waveforms using Relay Assistant software [12]. The test setup at Texas A&M University laboratory can play back six high voltages, two low voltage signals and more than 15 digital contacts. The signals were captured by the CBs and transmitted to the concentrator.

Two Circuit Breaker Monitors have been tested in a field setup at Center Point Energy's substation. The IEDs were set up at breakers, which operate on a 345kV line. Fig. 9 shows a field placement of CBMs.

The breakers are located at an approximate distance of 150m from the control house. They are connected to the Substation PC through a wireless RS232 network interface in point-to-multipoint configuration. The master side software is installed on the substation PC and initialized to start data reception. In the normal work condition one cannot expect more than few events per month because breakers in this substation operate rarely. In the test phase one may implement special features to enable efficient testing of Circuit Breaker Monitor devices. An automated log file procedure has been set up. It assures that the CBM records and sends a data file in equal time intervals. It is observed that one record per day is enough to check current status of a CBM. In this way one can collect and compare large number of records in relatively short period of time.

Figure 9: CBM device installed in switchyard

The CBM Client software that executes automated analysis was tested using data retrieved from CBM devices. Some test cases came from lab simulation and some from field recordings. Software enables the following features:

- Visual topology monitoring - showing automatically CB status changes on one line diagram.
- Visual sequence of events monitoring - showing time line, where event is marked together with corresponding time stamp and source of event record.
- Detailed maintenance report - containing detail information about abnormal behavior of any signal, suggesting possible causes of troubles and providing instructions for maintenance.
- Sequence report – recognizing beginning of new sequence and listing each event as it comes with brief description containing status of breaker and time stamp. After sequence is finished it will state the cause of sequence initiation and quality of executed sequence, whether it was correct or not.

VI. Conclusions

Using the CBM and automated analysis software solution described in this paper, new information could be provided to several utility groups. The following is a summary of the benefits achieved with this new solution.

- System operators: A more detailed message whether the breaker operated properly, what caused the operation and whether the related switching sequence was completed successfully? This will give operators needed confidence to override breaker lock-outs in the case the switching operation outcome is not warranted.
- Protection engineers: A detailed timing of the clearing sequence with precise time stamps of all switching events. This will allow protection engineers to trace the required details of the breaker opening/closing sequences needed to verify accuracy of the time coordination between relay and breaker operations during fault clearing.
- Maintenance staff: A precise recording of control circuit signal waveforms taken with GPS synchronization. This will provide maintenance staff with detailed behavior of CB operating mechanism leading to more reliable decisions about the need to repair or perform routine maintenance on one or multiple breakers.

VII. Acknowledgment

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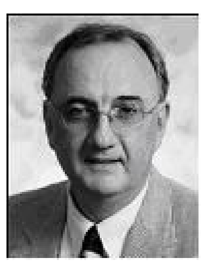
IX. Biographies

Maja Knezev (S'03) received her Dipl. Ing. degree in electrical engineering from the University of Novi Sad, Serbia, in 2004. She is currently pursuing the M.S. degree 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.

Zarko Djekic (S'03) received his Dipl. Ing. degree in electrical engineering from the University of Novi Sad, Serbia, in 2004. He is currently pursuing the M.S. degree in the Department of Electrical Engineering, Texas A&M University, College Station. His research interests include power system monitoring, protective relaying, relay testing and substation automation.



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 Corp., Pittsburgh, PA, 1979-1980 and the Energoinvest Company, in Europe 1980-1986. He was also a Visiting Associate Professor at Washington State University, Pullman, 1986-1987. 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. Dr. Kezunovic is a member of CIGRE and Registered Professional Engineer in Texas.