Troubleshooting Protective Relay Operations Using Field Recorded Waveforms

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Abstract—The paper describes the use of automated analysis reports and field recorded signals in troubleshooting protection system operation. Utilizing automated analysis of field-recorded data dramatically expedites the process of setting up test equipment and choosing and creating test. Automated analysis reports provide both the analysis results and recorded waveforms. Analysis results can be utilized to select test locations in the power system of interest and choose the right simulation conditions. The recorded waveforms can generally be used in two ways: for fault playback simulation and as a reference to calibrate simulation model.

Several tools and methods on how to utilize recorded signals for the fault playback and simulation calibration are presented. The tools and methodologies are discussed from through examples on field data recorded in a real power system.

Keywords: electromagnetic transients, application testing, power systems, protective relays, digital simulators, automated analysis.

I. Introduction

AUTOMATED analysis of field-recorded data captured by substations IEDs enables a new approach to troubleshooting power system protection operation [1,2]. The proposed approach utilizes field recorded waveforms (voltage, current) as well as the other relevant signals such as communication channel statuses, relay trip, breaker aux contacts, etc. The analysis reports can quickly identify the system protection failure and thus dramatically reduce the time needed for initiating the troubleshooting procedure.

The paper describes various steps in the use of field-recorded data and analysis results in troubleshooting protection system operation [3]. First, the analysis results and data are used to set up the simulation environment with a goal of repeating the problem through waveform replay. This is often referred to as fault playback. In addition to using recorded transients of analog waveforms, the simulation should be capable of providing other recorded signals such as the status of the protection scheme communication channels and circuit breakers. The following issues related to the direct use and management of field-recorded data for the replay purposes are addressed in details: 1) what are the limitations of the test equipment; 2) how the recorded waveforms need to be processed before they are used for replay

The analysis reports and field-recorded data provide information that can be used for calibration of the available system simulation models. Once the model is calibrated and the simulated waveforms match the ones recorded in the field, one can proceed with sensitivity study and continue troubleshooting utilizing now the calibrated system model and simulated waveforms. The paper illustrates such an approach with practical examples.

II. Background

Typical monitoring of power system protection operation assumes use of digital fault recorders. More recently, digital protective relays offer capabilities for recording the disturbances as well. The signals being monitored and recorded are line currents and voltages as well as protection-related status signals such as relay trip, breaker auxiliary contact, carrier signals, etc. The analysis of the monitored and recorded data is essential for correct identification of the causes, classification of the impacts, and selection of the best strategy for system restoration.

This paper focuses on the methodology on how to utilize field-recorded waveforms and automated analysis results for troubleshooting system protection operations. The automated analysis results are the key to dramatically expedite identification of important field-recorded waveforms and quick identification of initial information on the conditions related to the power system disturbance. The methodology on how to use the recorded waveforms for relay testing is presented next.

The methodology for utilizing field-recorded data for troubleshooting of protective relays assumes the following steps:

- *Automated analysis*. Recorded data are collected and analyzed automatically. The analysis helps quick identification and recognition of power system disturbances and related system protection operations that need to be checked (e.g. relay failure).
- *Fault playback.* Recorded data identified as events related to system protection failure should be readily available and used for playback to protection relay to verify that

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such conditions would cause relay to fail again.

- *Model Calibration and Simulation.* Recorded data and information obtained through automated analysis are used for calibration and/or development of the system model that can be used to simulate similar power system events. Once the model is calibrated and verified several sensitivity tests can be generated utilizing simulation.

The implementation concept and data path for use of field-recorded recordings is shown in Fig. 1. Waveforms recorded by IEDs (DFRs or digital relays) are automatically acquired and stored in a database. Automated analysis of new event data is performed and the reports are added to the database. Analysis reports provide information on event classification and priority as well as the event origin. All event-related parameters can be used and combined in the database search criteria. Additional automated analysis can be focused on the system protection operations. The analysis should be able to recognize and evaluate protective relay related events to identify relay operation failures.

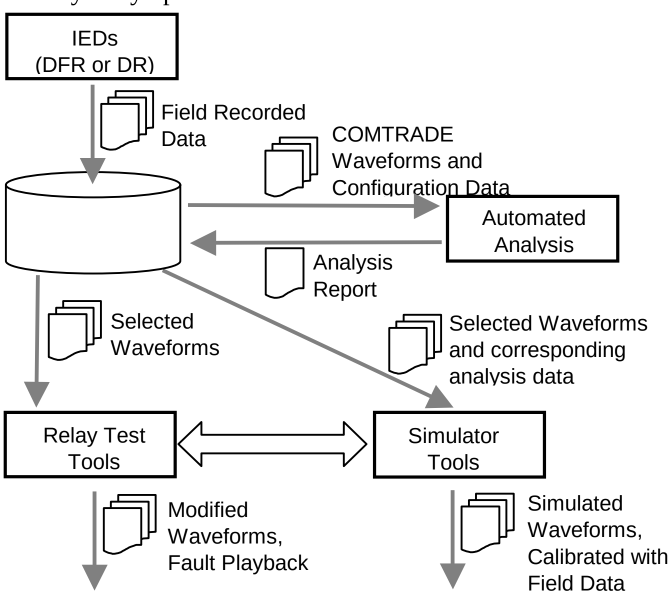

Fig. 1. Utilizing IED field-recorded data and automated analysis for troubleshooting of protective relay operations: 1) fault playback; 2) simulation with model being calibrated by the field data

The field-recorded data can be used in two ways for testing and troubleshooting protective relays: 1) fault playback and 2) simulation. For the fault playback, recorded waveforms are modified and prepared for feeding the relay in order to repeat the same conditions as during the real event. Several modifications of the originally recorded waveforms may be needed: re-sampling, signal level adjusting (primary to secondary), filtering to remove higher harmonics, extending pre- and post-fault duration etc. Some of these interventions are related to the limitations of test equipment (e.g. re-sampling) and some of them are required due to relay behavior (e.g. some relays required at least 30 cycles of "normal" pre-fault conditions prior to fault playback).

Another use of field-recorded waveforms in relay troubleshooting is when a system model is used for simulating power system faults. Recorded waveforms and analysis reports are used for the model calibration and tuning. The waveforms and analysis results are used for comparison with the simulated waveforms and conditions. The model parameters can be adjusted to match the waveforms obtained in field. Once calibrated, the model can be used for several simulations to obtain waveforms around the conditions being troubleshot as well as to simulate faults at different locations and/or circuits (e.g. parallel lines).

III. Automated Analysis of Field Recorded Data

Automating the processing and analysis of monitored and recorded data is the key for speeding up the restoration after power system disturbances. Several functions can and should be automated [4,5]:

- Collecting the disturbance data and making it readily available for the analysis;
- Identifying the main disturbance features;
- Performing the analysis;
- Disseminating the analysis results.

A. Collecting the disturbance data

Communication and data integration are going through major changes as the IED vendors are improving existing and making new devices with features to enable better interoperability and connectivity. The main goal is to be able to access the substation data, in this case disturbance related recordings, as soon as possible and make it available for the analysis. The reliable and fast communication infrastructure as well as automated data retrieval is essential. Data format is also an issue and it is highly desirable that all the substation data be converted and kept in a unified data format. For the power system disturbances, the widely accepted data format is COMTRADE [6].

B. Identifying main disturbance features

Once the recorded data has been acquired and convert into an accessible data format some pre-processing is needed in order to prepare the data for the analysis. First task is to determine the circuit where the disturbance took place. In some instances this task is straight forward, for example if the recording comes from a distance relay [2]. If the recording contains monitored data from several circuits (which is the case with DFR recordings) the pre-processing needs to determine the affected circuit [1]. For the selected circuit, the pre-processing should determine and calculate the following parameters:

- Exact time points of the disturbance instance and clearance. With these time points the whole recording can be divided into pre-fault, fault, and post-fault intervals;
- Fundamental frequency values for currents and voltages during all the disturbance related time intervals (pre-fault, fault, post-fault);
- Time points and statuses for the protection monitoring signals if they are available. This includes: relay trip signals, breaker auxiliary contacts, blocking send and

receive, transfer trip, etc. More elaborate analysis requires these signals to be monitored and recorded.

C. Performing the analysis

Different depth of the analysis can be performed. It is important to note that this paper focuses on the automated analysis, which is the key for speeding up the process of locating the data directly related to the power system disturbances of interest. There are several reasons why the recording devices can trigger. The main requirement for the automated analysis is to classify the recordings and assign priorities. The user can focus on the data that are recognized as high priority data that corresponds to an actual power system event of interest: faults with some issues during the clearing, or faults where protection has failed.

TABLE I
SAMPLES OF EVENTS THAT CAN BE RECOGNIZED BY AN EXPERT SYSTEM ANALYSIS

Event	Description
Manual trigger	Detects change of status on the external start.
Relay Trip	Detects change of status on trip digital channels.
Relay Slow	Detects relay trip, and relay pick-up time is greater than the settings (e.g. 4 cycles).
Relay Failure	Detects relay trip when there was no fault, or relay did not tri and there was a fault.
Breaker open	Detects change on status (open, close) or check if current measurements are lower the preset settings.
Breaker slow	Detects breaker open and breaker open time are greater than the setting (e.g. 8 cycles).
Restrike occurs	Detects beaker open and breaker current through that breaker is not zero.
Reclose unsuccessful	Detects multiple relay trips in the record, and phase current is zero at the end.
Wrong carrier signaling	Detects if relay trip and carrier signals are in disagreement.

The analysis can be implemented in many different ways. More elaborate analysis should utilize knowledge base expert systems approach where several expert system rules can be derived [4]. The knowledge base contains the facts on analog signal values as well as the their relationship to the status signals.

Typical knowledge base has the following rule types:

- Fault detection (fault, no fault).
- Fault type rules (ground, non-ground).
- Fault classification (line-to-ground, two line-to-ground, three line-to-ground, line-to-line, three-line).
- Clearance related rules (local, remote, failure).
- Breaker related rules (open, close, recluse, failure).
- Relay related rules (trip, no-trip, slow, failure).
- Protection schema related (comm. channel operation).
- Fault location related (exact point of fault)

Example set of events that can be recognized by the expert system analysis is given in Table I. The table displays only a subset of possible events that can be recognized. Depending on various relay applications and protections schemes different expert system rules can be implemented and allowed recognition of different events.

D P R A   E V E N T   R E P O R T

*** Event Origin ***
DFR Assistant Client : Client No. 1
Substation : Substation No. 22
DFR Native File Name : ZQ1757
Affected Circuit: Transmission Line #27

*** Event Description ***
Transmission Line #27is the circuit with largest current disturbance.
The disturbance is a phase B to ground fault.
The fault is cleared by the protection system at this substation!

*** Fault Location ***
Fault is located 21.54 miles from Substation No. 22.

*** Protection System Operation Analysis ***
Backup relay operation starts at 0.0337 sec [2.0202 cycles]
and ends at 0.0487 sec [2.9202 cycles].
The middle 52B contacts operate at 0.1438 sec [8.63 cycles].
The bus 52B contacts operate at 0.0537 sec [3.2202 cycles].
The bus breaker status change after tri is applied is 6.2 [cycles].
The middle breaker status change after trip is applied is 1.6 [cycles].
The bus breaker is slow. Check the bus breaker for maintenance.

*** Event Summary ***
Trigger Date and Time: 12-12-2003 15:36:30.923
Event Description : BGND_FAULT
Fault Location : 24.54 [miles]
Fault Resistance : 3.68 [Ohms]
Disturbance Duration : 24 [ms]
DC Offset : 271.13 [%]
Event Outcome : LOCAL_CLEARANCE
Breaker Operation : 1st, CB_OK
Breaker Operation : 2nd, CB_OK
Relay Operation : PRIM, RL_OK
Relay Operation : BACK, RL_OK

*** Line Currents and Voltages ***

Prefault Values:	Fault Values:	Postfault Values:
I0 = 0.0087 [kA]	I0 = 24.19 [kA]	I0 = 0.001 [kA]
Ia = 0.2076 [kA]	Ia = 0.801 [kA]	Ia = 0.000 [kA]
Ib = 0.1868 [kA]	Ib = 22.83 [kA]	Ib = 0.000 [kA]
Ic = 0.1672 [kA]	Ic = 0.272 [kA]	Ic = 0.000 [kA]
V0 = 0.006 [kV]	V0 = 0.086 [kV]	V0 = 0.001 [kV]
Va = 283.70 [kV]	Va = 272.6 [kV]	Va = 282.2 [kV]
Vb = 284.90 [kV]	Vb = 106.4 [kV]	Vb = 282.8 [kV]
Vc = 283.80 [kV]	Vc = 272.7 [kV]	Vc = 283.6 [kV]

Fig. 2. An example of the analysis report: all the values from the event summary will be stored in the database, which allows easier search and different search criteria. These values can also be used for the simulation set up and model calibration.

An example of the analysis report is given in Fig. 2. The report is returned to the database and assigned to the corresponding recorded data. The report contains information related to the line being identified as a circuit with the highest disturbance. Experiences in the field suggest that the analysis should be performed for all the lines/circuits being monitored by DFRs/IEDs. This approach would enable easier spotting of the faults located beyond the buses where the data have been collected and recognizing if several lines have been involved. Other field experiences suggest extraction of as many as possible of different disturbance and fault related parameters that can be forwarded to other applications: fault duration, DC offset at the moment of fault occurrence, fault resistance, etc.

D. Disseminating the analysis results

Once the analysis has been completed both the recorded data and corresponding analysis report are available and stored into the centralized database. Depending on the outcome of the analysis and priority classification several types of notifications can be sent (email, pager, printer, fax). In addition the database should be accessible via remote user interface. The most convenient approach is to utilize a web application that allows all authorized personnel to access the recorded data and analysis results using a standard web browser [1].

The key benefit of automated analysis is providing all the field-recorded data in a centralized database. User can query the data by specifying search criteria using the attributes such as substation, line, breaker, relay, fault type, event outcome, etc.

IV. Fault Playback Requirements and Examples

Once a relay miss-operation event has been identified and there are field-recorded waveforms available, one can proceed with the troubleshooting procedures utilizing the recorded waveforms and the acquired knowledge on the event. The strategy used for solving the problems can be summarized as follows:

1. Convert all the event waveforms to COMTRADE file format [7].
2. Re-sample the waveforms to 10KHz. Relay test set used requires 10 kHz sampling rate [8].
3. Extend the pre-fault duration if needed.
4. Set up a relay in the lab with the same settings as the field relay that failed.
5. Play the waveforms into the relay in the lab. Lab relay should respond the same way the field relay did.
6. Analyze the waveforms; determine which element settings need to be changed to make sure that the relay will operate properly next time.
7. Put new settings in the lab relay
8. Play the waveforms into the relay with new settings. Relay should not miss-operate. If unsuccessful repeat 6-8. If successful, end of troubleshooting.
9. If successful, fix the setting of the relay in field.

The following sections will discuss this approach through three different cases that occurred in real power systems. Two of the problems were resolved using data that was recorded by DFRs. The third problem had no DFR data and was resolved by playing data that was recorded in the problem relay. Each case had unique issues that needed to be dealt with in order to analyze the relay problem.

A. Fault Playback: Case #1

The first case was a miss-operation of a breaker failure relay (BFR) that resulted in the unnecessary tripping of a 230kv bus and the lines on that bus. In this case there was a close-in fault on one of the lines. The relays correctly identified the fault and sent a trip signal to the breaker and to the associated BFR. The breaker properly cleared the fault, but the BFR continued to time out until it tripped. After analyzing the DFR record, it was noticed that the breaker properly cleared the fault, but the CT continued to supply a decaying DC current to the BFR after the breaker was open. This is an old issue and was not surprising. This was accounted for when BFR relays were electromechanical plunger type relays. The relay that operated however was a static relay and it was a surprise when it did not reset after the breaker opened. The DFR data were played into the BFR installed in field and into a test BFR in the lab and verified that both the relays failed in the same manner during the test. After adding the fix to the element, waveform playback was used to verify that the repaired element did not operate. In order to operate the breaker failure relays with the test set, it was needed to use a recorded digital quantity to operate an output on the test set, which applied a voltage to the trip input on the test relay at the proper time.

B. Fault Playback: Case #2:

The second case involved line differential relays on a short 230kv line. The differential relays false tripped on inrush when a bank of transformers external to the zone of protection was energized exposing the relays to large inrush currents. DFR data was used for the playback. In this case data from DFRs at both terminals was used for end-to-end playback. The DFR data from both terminals had to be time synchronized in order for the tests to be valid. This testing required data from two different digital fault recorders, and the data had to be properly time synchronized. Having the recorded data in COMTRADE file format and tools for handling the waveforms (merging signals from two DFR recordings, synchronizing, re-sampling) was critical for successful troubleshooting in this case.

C. Fault Playback: Case #3:

The third case involved a microprocessor-based relay set for single pole operation on our 500kv system. The problem was identified while performing system fault tests on new series capacitors at a station 159 miles away. The lines to the station where the faults were applied were adjacent to the line with the problem relay and so the faults were in the reverse direction for that relay. The zone 2 element in the problem relay would momentarily operate and send a permissive signal after the faulted phase at the remote station was opened. Since zone 3 is set for a reverse reach, it was expected that zone 3 rather than zone 2 should have operated. On analyzing the fault record it was observed that the impedance at the relay location was changing (swinging) as the system was stabilizing after the remote faulted phase was opened.

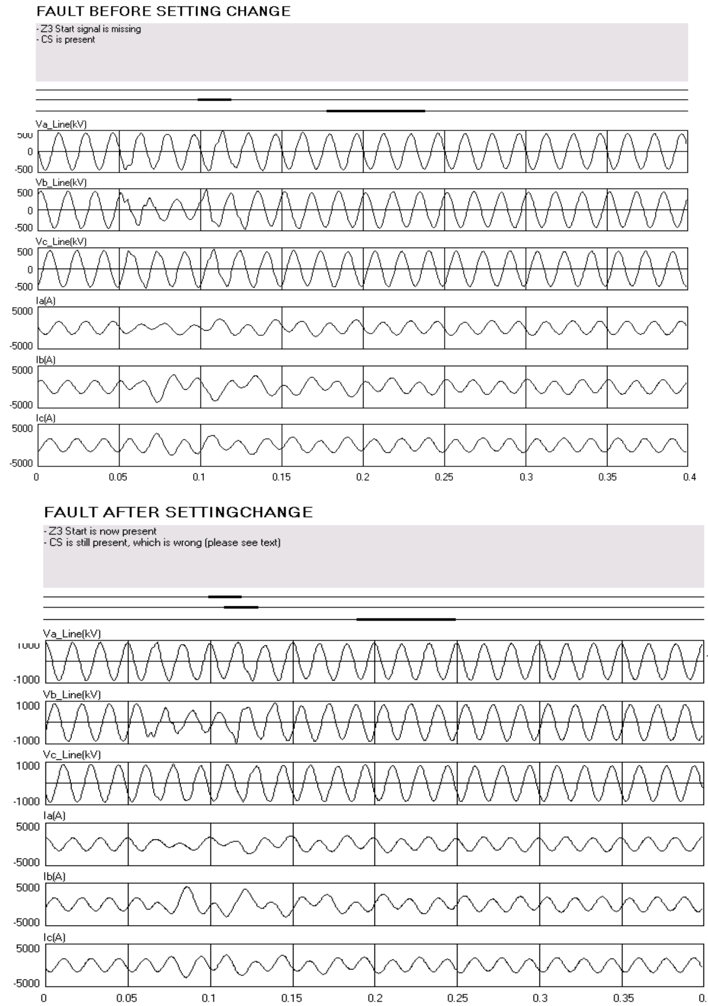

Fig. 3. Playback Case #3 waveforms obtained from the digital relay: before and after the settings have been fixed.

The line load in combination with these system oscillations caused the momentary operation of the zone 2 element. For this case the data from the relay was used for the testing. The data had to be re-sampled for the test set, and the test set had to loop the pre-fault data for at least 1 second prior to the fault event in order to reset the switch onto fault logic. The relays performed under test exactly as they did for the actual event. In order to determine the setting corrections required to solve this problem, relay test software needed to be used to plot the impedance trajectory over time during the fault event. This plot was then compared to the characteristics of the relay elements to determine where the impedance entered the zone 2 element and missed the zone 3 element. The impedance during the initial fault operation was in the zone 3 direction, but just beyond the set reach. It moved into the zone 2 characteristics after the faulted phase was cleared and the system was stabilizing. Based on this analysis a directional blinder was moved and the reactive reach of zone 3 was increased. The relay was re-tested and operated correctly (please refer to Fig. 3.). After fixing the zone 3 start, the relay still shows carrier send (CS), which is wrong. This was fixed by adjusting the timer that locks out CS after zone 3 being detected.

These three cases represent three different requirements for playback testing. Case 1 required an accurate digital output to apply a trip signal to the BFR relay at the proper time in the fault event. Case 2 required end-to-end testing so the data from two digital fault recorders needed to be accurately time synchronized. Case 3 required play back of data recorded by the problem relay, but also required the additional step of plotting the impedance trajectory against the relay element characteristics in order to determine how to change the settings.

These are just three “real-life” test cases out of hundreds. Having all the data automatically converted to COMTRADE file format and available in the centralized database dramatically expedites setting up of the test environment needed for fault playback.

V. Use of Field-Recorded Data for Simulation

Use of the recorded data for simulation is illustrated through two cases described in the following sections.

A. Simulation: Case #1

This DFR event represents the response of transmission line parameters to a 69kV bus fault that occurred at one of the line terminals. This fault was part of a sequence of events that eventually caused bus CTs to saturate and, consequently, bus relaying miss-operation. The DFR recording was used primarily to determine the fault incidence point on the bus voltage waveform (see Fig. 4. displaying faulted phase A bus voltage) so that the DC offset content during the first fault could be determined. This information was used to help tune an ATP model representing the faulted substation bus [9,10]. The model was used to perform further investigations on CT saturation at that location, as well as generate saturated current waveforms for automated relay simulation and testing.

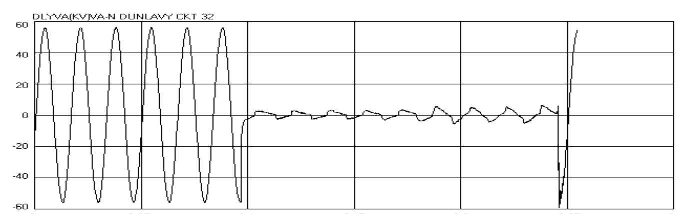

Fig. 4. Simulation Case #1 waveform obtained from DFR was used to determine parameters related to CT saturation.

B. Simulation: Case #2

The captured DFR event of example 2 represents a phase-C-to-ground fault on a 180-mile 345kV transmission line. The recording was used to verify an ATP model representing the same 345kV system and used to simulate signals for automated playback and testing of digital relays. The ATP output of the faulted phase current is shown for comparison. The simulated fault current duty of this event was verified in this simulation. Other tools and data, such as load-flow and short-circuit data, transmission line configuration and mutual coupling data, were also used to build and tune the ATP model prior to actual relay testing. Several tests were then generated utilizing the calibrated model.

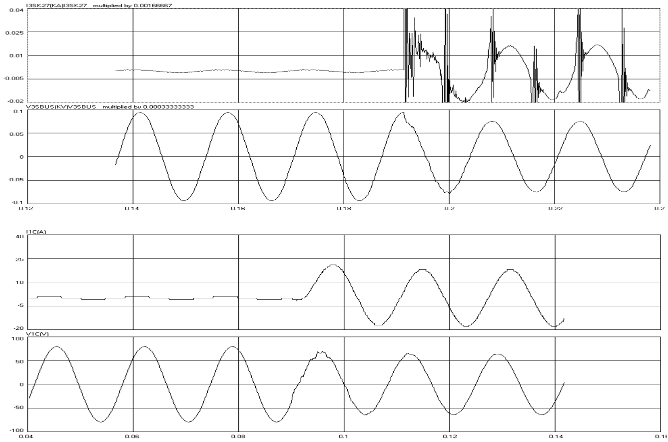

Fig. 5. Simulation Case #2: upper two waveforms obtained from DFR used to determine fault duty; lower two waveforms generated with the calibrated model.

Benefit of automated analysis for the simulation is easy locating of the relevant field-recorded data together with the extracted event parameters, which can be used for calibration and verification of the simulation models.

VI. Conclusions

Automated data collection and analysis of the field-recorded waveforms is essential for expediting the troubleshooting of protective relay operations. The analysis is important for quick identification and classification of the recorded waveforms.

Fault playback is important for repeating the problem in the lab conditions. The playback methodology was presented through three cases experienced in a real power system where the fault playback helped solving the problems. Field-recorded data and analysis results may be essential for calibrating and tuning the system model used in simulation.

The presented automated analysis can dramatically expedite process of locating the right field-recorded data that can be used for fault playback or calibration of the system models. All the data together with the analysis reports are available in a centralized database.

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VIII. Biographies

Mladen Kezunovic (S’77, M’80, SM’85, F’99) received his Dipl. Ing. Degree from the University of Sarajevo, the MS and PhD degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively.

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 IEEE.

Hyder DoCarmo (IEEE M’98), a native of Paraná, Brasil, has bachelor and master degrees in electrical engineering from Louisiana State University and Texas A&M University, respectively. Between 1998 and 2000, he worked as an electrical design engineer for Transocean Offshore Drilling, in Houston, TX. Since 2000, he has been a protection engineer in the Systems Operations group of CenterPoint Energy’s Substation Projects Department, also in Houston. Hyder is a registered Professional Engineer in the State of Texas, and a member of the System Protection Subcommittee of the IEEE Power System Relaying Committee. His current professional interests are transmission line and substation protection, applications and testing of microprocessor-based relay systems, and digital simulation of power systems.

Thomas S. Roseburg (M’91) received a BSEE from Washington State University in 1971. He began his career with Bonneville Power Administration in 1972 where he worked as a field engineer with Substation Construction Department. In 1975 he became a field engineer in System Protection Maintenance where he worked as a protection engineer in substations in Washington and Idaho. In 1988 he transferred to BPA’s Branch of System Protection Maintenance department in Vancouver, Washington where he works on protection issues on the BPA 115kv, 230kv, and 500kv systems. He is currently working at that position in Vancouver. He is a member of IEEE.

Michael Hofmann (M’92) received his degree in Physics from the University of Texas at El Paso in 1973. He was employed as an Electronics Engineer at White Sands Missile Range, NM, and has worked as an Electronics Engineer at Naval Undersea Warfare Engineering Station, Keyport, WA, and as Computer System Manager for David Taylor Naval Ship R&D Center, Bethesda, MD. He has been employed at Bonneville Power Administration in the Division of Laboratories since 1988. Mr. Hofmann works in the Protection and Control Section and specializes in advanced technology applications to power system protection engineering. Mr. Hofmann is a member of IEEE and CIGRE.

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He has been with Test Laboratories International Inc. since 1998 where he is a development engineer. His prior positions were with NIS-GAS, part of Petroleum Industry of Serbia, and University of Novi Sad, both in Novi Sad, Yugoslavia. His main professional interest is developing and implementing software and hardware solutions for industrial applications, especially in the field of electric power system engineering: analysis of fault records, transient testing of protective relays and digital simulators. Mr. Popovic is member of IEEE.