Assessing Application Features of Protective Relays and Systems Through Automated Testing Using Fault Transients

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***Abstract* — This paper presents a new approach to assessing application features of protective relays. The approach utilizes a test methodology based on the use of transients. Application features of protective relays, such as the response time and trip selectivity, may be extremely important when investigating relay misoperations or when purchasing new relays. These features are not readily known or made available in the relay manuals. The paper provides examples of how the test methodology may be applied and what kind or results may be obtained. It also discusses the requirements for the test tools to be used. A discussion of the test tools features that may be needed as well as the ways the tools may be applied to perform testing is presented as well. Conclusions about the needs for suitable test tools are given at the end.**

***Index Terms* — Application Testing, Automated Testing, Digital Simulators, Electromagnetic Transients, Protective Relays, Type tests**

I. Introduction

TODAY'S approach to relay testing relies primarily on the use of test sets capable of assessing the design properties such as the relay operating characteristic [1]. Such tests are useful in determining if the relay settings are properly calibrated. As much as such tests are useful for the mentioned purposes, their utilization for assessing application features such as the response time and trip selectivity are rather limited. The application features of a relay or relaying system become extremely important when investigating relay misoperations or when purchasing new relays not previously used on the power system of interest [2]. The question remains as to what may be the most effective way of assessing the application features of interest, both in terms of the testing methodology and the tools that support implementation of the methodology [3].

This paper addresses both issues: what may be the most appropriate methodology for application testing and what are the most cost-effective testing tools for doing this. The entire concept of application testing is somewhat new, and the paper first sets the stage of what type of information may be obtained through such tests. An example of performing such tests on five commercial distance relays is given to illustrate the type of the results that may be obtained [2]. It is shown that application testing may reveal some very interesting behavior of some of the relay designs. One discovery is that, in the first zone, direct trip takes far more time than usually anticipated by reading the relay data from the manuals. In addition, it is noted that a simple trip/no trip test reveals that some relays may have rather unreliable performance around the set point. Dispersion in the trip times when repeating given tests multiple times is also an interesting feature that can be discovered using application tests. The impact of such test results in designing relaying systems and evaluating their performance is discussed as well.

The core of the application-testing concept is the ability to reproduce fault transients that resemble very closely actual transients in the field. The transients may be obtained through simulation, or may be recorded in the field. The application testing method assumes that there is a testing tool that allows one to reply the transients into a relay or relaying system using standard test sets or customized amplifier systems. The replaying should be done automatically when a large number of tests are to be performed. The paper gives a description of a low cost solution for performing application tests. The solution is based on a standard PC and a transient program called ATP (Alternative Transients Program), which may be obtained as a freeware [4],[5]. An open-loop PC based simulator is utilized to obtain the multiple waveform sets by running ATP several times automatically. Each time the ATP fault parameters are changed to account for a new fault case [6]. Once a batch of test waveforms is formed, an automated procedure for testing the relays is initiated.

The paper starts with a discussion of the two basic types of tests, namely phasor-based and transient-based. An example of the results of the transient-based testing is given. The requirements for performing transient tests are identified. As a result, the requirements and solution for testing tools are presented. A set of conclusions regarding the benefits of transient-based testing is outlined with a reference to the software and hardware solutions that meet the requirements.

II. Background

The relay behavior can be analyzed in the context of various influential factors: power network applications, fault

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characteristics, relay algorithms, etc. The analysis reveals that the relay behavior can be considered as either predictive or random [3].

A. Predictive Behavior, Steady-State Phasor-Based Methods

If the input signals are ideal sine functions, the relay algorithms have a predictive behavior. Many elements may affect the output, but the overall performance should be predictive. The operating characteristic of the relay can be obtained by recording operating points related to variety of input signals. Comparison of the measured and theoretical operating characteristic gives an assessment of the predictive relay behavior. This type of testing is called design testing [1].

Currently, the prevailing testing practice is to use steady-state phasor-based methods. In such tests, the test signals are usually pure sine waveforms. If the test signal changes, the change is much smaller than the resolution of the relay. Such testing suits well purposes aimed at verifying and calibrating relay settings and is not aimed at evaluating relay transient performance [1].

B. Random Behavior, Transients-Based Methods

Random behavior of the relay is related to transients. In this case, the relay behavior may not match the one observed for phasor-based test waveforms. In particular, the relay response and the operating time are variable. Measuring the direct-trip time and determining if the relay should have tripped constitutes the assessment approach in this case. This type of testing is called application testing.

Most vendors of the relay test equipment offer computer-based test sets capable of performing steady-state tests. Many of the test sets also provide capability for dynamic testing and some include rudimentary transient testing capabilities. Test equipment fully capable of transient testing is rather rare and expensive especially in the case of the real-time simulators [7].

C. Results from Transient Testing of Distant Relays

A need for testing of protective relays with transients can be presented trough illustrative examples presented in the following subsections.

1) Example I - Statistical Approach, Operating Time

An example of results that can be obtained by executing application testing on one relay using transients is given in Table I. In this example, different test cases were simulated for different type of faults, and for different fault locations on the line. Each test was repeated 30 times, and statistical methods were used for determining operating times for the tested relay. One can notice very interesting results with respect to differences in operating times for different types of fault as well as to differences between maximal and minimal values of operating time for a same fault case.

Applying the steady-state phasor-based methods cannot enable recognizing and assessing of these interesting features. It requires a statistical approach, using multiple-run testing with transients. Ability to generate and replay a large number of different test cases is a very important requirement.

TABLE I
EXAMPLE OF STATISTICAL TESTING

Type	Loc %	No. T	AvrgT [ms]	MaxT [ms]	MinT [ms]	Devtn [ms]
A-G	50	30	20.68	23.12	17.94	1.49
A-G	75	30	22.75	25.04	20.34	1.48
A-G	80	30	25.67	41.72	23.62	3.17
A-G	90	0	*****	*****	*****	****
A-G	95	0	*****	*****	*****	****
B-C	50	30	20.57	22.90	18.46	1.36
B-C	75	30	26.04	28.50	23.66	1.44
B-C	80	30	35.23	66.26	25.02	12.36
B-C	90	0	*****	*****	*****	*****
B-C	95	0	*****	*****	*****	*****
ABC	50	30	19.21	20.44	18.34	0.61
ABC	75	30	24.68	25.40	23.68	0.54
ABC	80	30	25.63	27.24	24.26	0.81
ABC	90	0	*****	*****	*****	****
ABC	95	0	*****	*****	*****	****
BCG	50	30	20.27	23.06	17.98	1.45
BCG	75	30	26.10	28.58	23.66	1.47
BCG	80	30	34.53	66.18	24.86	12.28
BCG	90	0	*****	*****	*****	*****
BCG	95	0	*****	*****	*****	*****

2) Example II – Comparative Analysis, Operating Time

Another example of results obtained by application testing is given in Fig. 1. The figure depicts a comparative analysis of operating times vs. fault location for four different relays. Operating times shown in the Fig. 1. are obtained statistically, after several tests cases were repeated. Relays were expected to operate in zone one (all faults located in first 85% of the line). An interesting outcome was that the operating time, for some relays, became much longer than it was expected for the first zone. Such testing also requires multiple-run testing and ability to generate large number of different test cases.

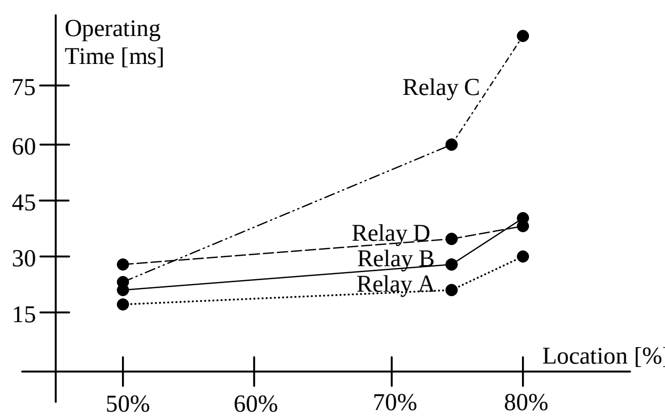

Fig. 1. Example of Comparative Analysis

3) Example III – Trip/No Trip Evaluation

In third example, an evaluation of relay trip/no trip operation has been done for five relays (Table II). Relays were tested with transients corresponding to different types of faults and different fault locations. Relays were expected to operate only in cases when the fault location was inside first 85% of the line (Zone I operation).

As it can be seen in Table II, the relay B did trip for transients corresponding to faults located out of the zone of protection. In one case, this relay misoperated for every single test run.

As in previous two examples, to evaluate features such a trip/no trip response, one needs to use multiple-run testing with transients. An important requirement is to be able generate a large number of different test cases by taking into account several parameters that describe faulted conditions.

TABLE II
NUMBER OF TRIPS OUT OF 30 TESTS

Fault Type & Locations	Relay A	Relay B	Relay C	Relay D*	Relay E*
A-G 50%	30	30	30	0	0
A-G 75%	30	30	30	0	0
A-G 80%	30	30	30	0	0
A-G 90%	0	**20**	0	0	0
A-G 95%	0	**19**	0	0	0
BC 50%	30	30	30	30	30
BC 75%	30	30	30	30	30
BC 80%	30	30	30	30	30
BC 90%	0	**12**	0	0	0
BC 95%	0	0	0	0	0
ABC 50%	30	30	30	30	30
ABC 75%	30	30	30	30	30
ABC 80%	30	30	30	30	30
ABC 90%	0	**30**	0	0	0
ABC 95%	0	0	0	0	0
BC-G 50%	30	30	30	30	30
BC-G 75%	30	30	30	30	30
BC-G 80%	30	30	30	30	30
BC-G 90%	0	**14**	0	0	0
BC-G 95%	0	0	0	0	0

* Relays D and E did not have a ground-protection element

It is not hard to imagine that the several other interesting features could be identified, measured, and compared if more different cases, with variation of additional parameters (for example, varying fault incidence angle and fault resistance) were generated.

4) *Requirement for the Methodology*

In the case of a purchase of new relays, one can use various test cases to assess the parameters like trip/no trip operation under certain conditions, to compare the results, and to narrow the choices for the final decision.. Typically, for these cases, application testing is done using transients obtained trough simulation.

In the case of troubleshooting misoperation, testing starts with transients recorded by DFRs when relay misoperated. More comprehensive troubleshooting requires generation of additional test cases generated by simulation where transients are obtained by varying parameters of the original fault [8].

In both cases, to develop and implement methodology for application testing using transients, it is required that the chosen methodology utilizes automated means to perform multiple-run testing as well as generating a large number of different test cases.

III. APPLICATION TEST REQUIREMENTS AND SOLUTION

This section discusses requirements and solutions for the testing tools used to perform application tests.

A. *Requirements*

Application testing is based on use of transients for testing protective relays in order to simulate the behavior of the power network during the faulted conditions. Generally, there are two ways of creating tests for transient testing of protective relays: using transients obtained from recorded waveforms and generating transients by simulation.

As discussed in the previous section, requirements for the application testing are the ability to perform multiple-run testing as well as to generate large number of test cases by simulating the desired conditions automatically. To facilitate these additional requirements, a system for testing should provide means to automatically perform tests, obtain results, and generate and archive test reports.

The requirements for the system for application testing are summarized bellow:

- Possibility to import waveforms from native file formats for different types of recording devices.
- Availability of several signal-editing features to enable customizing prerecorded transients.
- Flexibility of utilizing customized interface for simulation tools such as ATP.
- Possibility to generate the tests automatically by utilizing simulation tools.
- Capability to perform automated testing.
- Ability to create test reports automatically.
- Capability for high-performance waveform reconstruction with respect to D-to-A resolution and sampling rate.
- Possibility to use high power voltage and current amplifiers.

B. *System for Application Testing*

Architecture of the system, which meets above-mentioned requirements for application testing with transients, is shown in Fig. 2.

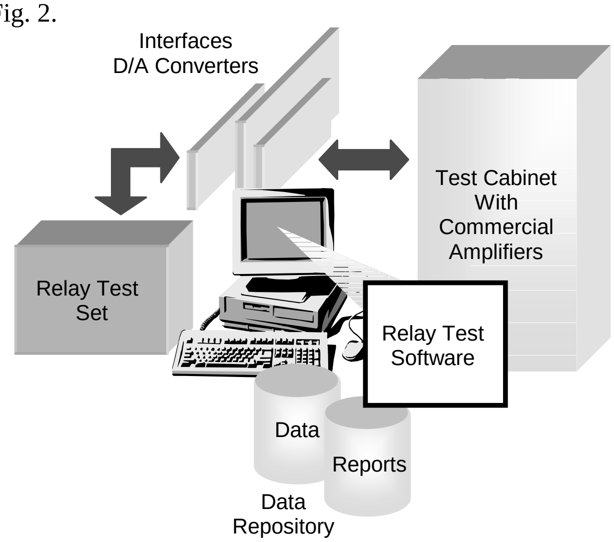

Fig. 2. The architecture of a PC-based open-loop simulator

Test system is a PC (personal computer) based open-loop simulator [9]. PC platform was selected due to its price, popularity, and performance. Simulator hardware can be interchangeable with the possibility of using either existing test sets or custom solutions. Relay test software should be easy to use and should not require substantial investment.

Simulator used for application testing should be able to utilize both recorded (obtained from DFRs) and simulated (obtained from EMTP/ATP) waveforms. An easy-to-use GUI with signal editing features for waveform processing, and test results visualization should be provided. The integration with transient simulation programs should be supported.

IV. Selection of Testing Tools

Efficient testing requires hardware and software tools designed or customized for automated testing. The most important automation aspects are: test preparation, test execution, result collection, result processing and result reporting. These requirements are aimed at reducing the time and cost of testing, while increasing the accuracy and reliability of the test results.

Automating the test result reporting is very important aspect of the testing. Both collecting the relay responses and generating the test reports must be automated. While collecting the relay responses, the following data must be recorded: relay response (trip/no trip), relay trip time and relay zone of operation. The test report should include scenario data, test data and relay data. Finally, performance indices such as the number of failures, the number of misoperations and the operating time should be calculated and included

A. Software Tools

The software tool the mentioned requirements consists of four modules [9]: 1) import filters for reading several waveform file formats (COMTRADE, ATP, native DFR) and creating arbitrary test waveforms; 2) waveform processing and editing (cut/paste, copy, crop, insert, rescale, resample, invert, pre- and post-fault extension etc.); 3) user-friendly use of simulator functions (displaying waveforms, reviewing test results, editing test reports, signal massaging etc.); 4) automated waveform replaying that includes drivers for various supported I/O hardware.

Handling and searching DFR files can be a difficult issue. It is extremely important that DFR files obtained in the system are well organized. Master station software provided by DFR vendors can be used for this purpose. There are more advanced software solutions that provide automated analysis, sorting, archiving, and reporting [10]. The records, together with the reports are stored into the centralized database and available for easy search and retrieval.

In addition, an easy integration with ATP and ATPDraw is utilized by use of a special option called BGEN (Batch Generator) [6]. BGEN is an add-on module that facilitates an automatic way of generating several test cases and reduces time needed for both training on how to use the simulation tools and for producing actual test waveforms.

B. Hardware Tools

As shown in Fig. 2., simulator architecture allows for interchangeable output hardware (a relay test set or a custom D/A converter with commercial amplifiers, etc.).

A selected PC-based open-loop simulator implementation supports two output hardware platform options [11]:

Option I – use of an existing test set, for example AVO test set PULSAR [12]. Two-set, three-phase simulator is available for applications requiring back-to-back testing of two transmission line relays needing low input power.

Option II - Customized I/O interface and user-selected commercial high-power amplifiers as the output hardware. Two-terminal, three- and four-phase simulators are available for applications demanding more output power [11].

The main characteristics of the I/O hardware for both simulator versions are listed in Table III.

TABLE III
I/O HARDWARE CHARACTERISTICS

Characteristic	Hardware option I	Hardware option II
Comm. interface	GPIB	Custom
Vertical resolution	13 bits	16 bits
Sampling freq.	50 µHz - 20 kHz	5 Hz - 40 kHz
Over-sampling	No	Yes
Current output	30 A rms, 150 VA	180 A peak, 1550 W
Voltage output	300 V (rms.)	120 or 300 V (rms.)
Configuration	1-, 2- or 3-channel	1-, 2-, 3- or 4-channel

Use of an existing test set has its benefits, especially in the situations when the user already has one, or when the portability during the testing is required. The main disadvantages are the low power of the amplifiers, lower D/A conversion resolution, and limitations related to the sampling rates. Slow communication interface, which is typically a serial type of interface, introduces another inconvenience such as long-time downloading of test waveforms to a test set, and generally long-time executing of test sessions when running several test cases.

Second option, based on a custom communication interface and 16-bit D/A conversion offers much more flexibility in meeting the application testing requirements. Higher D/A resolution, with a possibility of selecting different sampling rates up to 40kHz, enables reproducing transients more accurately. The amplifier selection allows reproducing signals with high signal power, which enables wider spectrum of simulated test conditions. This option is ideal for test laboratory uses, and the cost can match the price range of the existing test sets, and in some instances is even lower. Different selection of amplifiers could make this option also suitable for the use when portability is required.

V. Application Testing Using Recorded Waveforms

Fig 3. depicts the software and hardware setup needed for application testing using recorded waveforms. Typically, recorded waveforms are coming from monitoring devices such as digital fault recorders (DFR).

The selected software has several import filters and can easily read recorded waveforms from different type of sources. Native file formats for the most widely used DFR types are supported as well as COMTRADE file format [13].

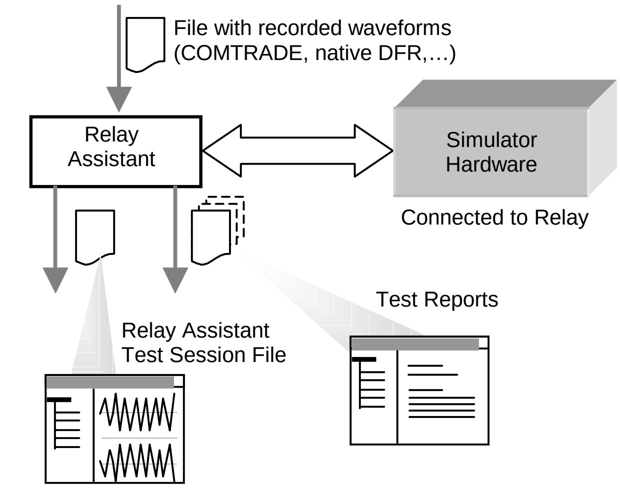

Fig. 3. Test setup for application testing using recorded waveforms

In practice, a situation when imported DFR file can directly be used for testing is very rare. Typical problems are signals in different range, inverted signals because of the wrong wiring, short pre-fault and/or post-fault duration, noise, etc. The software is equipped with several software features for editing the waveforms. Once the waveforms are imported into the software, they can be rescaled, filtered, inverted. There are also more advanced features such as extending of the pre- and/or post-fault for a given number of cycles, resampling, reconstructing waveform of a missing phase. More details on test waveforms can be obtained using the tools for displaying the signal spectrum, calculation of the steady state parameters, and calculation and displaying of the sequence values.

All the mentioned software features help preparing the waveforms for transient test replaying. The test data are organized and saved in a test session file. One session file can contain several tests, and each test can contain different waveforms. Session and waveforms files are stored to the database and reused when needed.

During the tests, the waveforms from each test are automatically sent to the simulator hardware, which is connected to the protective relay. The outcome of the relay's behavior under the tested condition (trip, no trip), relay trip time, and relay zone of operation, are automatically obtained and saved in the report file repository for further use. Each test can be repeated a given number of times.

Using transients recorded by DFRs has its benefits for initiating the troubleshooting of misoperations, or evaluating relays under certain conditions in the system. Unfortunately, for more elaborate testing, it is unrealistic to expect that a sufficient number of test cases obtained using DFR file will be available.

Using modern DFR managing software tools can help because it provides means for locating DFR files by variety of parameters specified in the searching criteria: substation, line, type of fault, etc [10]. Even a reason for a relay misoperation can be identified. Use of such a tool, however, anticipates that it has been installed in the system for some time, and a database containing a large number of DFR files is created.

VI. Application Testing Using Digital Simulator

Test setup for application testing by simulating faults is shown in Fig. 4.

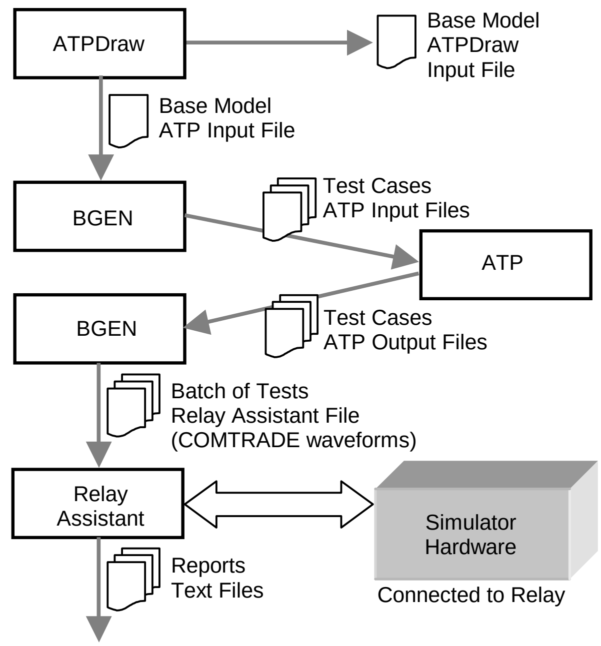

Fig. 4. Application testing setup

Base model of the power system is normally created by using ATPDraw graphical editor (Fig. 5.) [5]. User can manually incorporate faults in the model, run the simulation, and import the waveforms into the software.

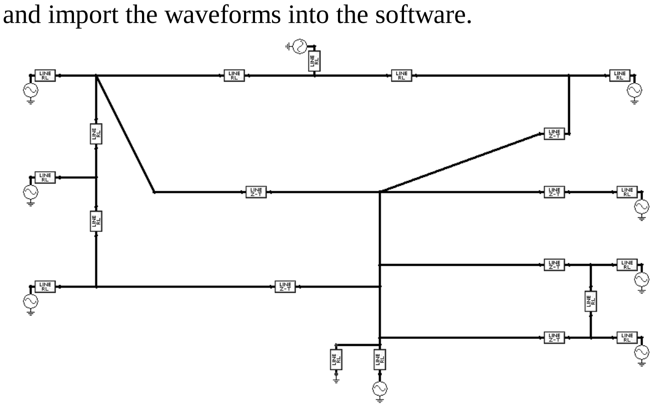

Fig. 5. An example of base model created in ATPDraw editor

BGEN reads the base model information from the ATP input file. BGEN is also used for specifying the measurements (relay position, CT and CCVT ratios). Once, the locations of the relays are specified, user adds descriptions of test cases. Each fault is specified by a set of parameters (type, location, initiation and clearing times, fault resistance etc.). The parameters are entered trough an easy-to-use GUI (Fig. 6.). Values for the parameters can be varied, so BGEN can automatically generate several test cases for the similar faults. For example, one can set the phase A-to-Ground fault, and than vary the location of the fault from 10% to 90% with a step of 5%c (total of 17 cases). One batch can contain different types of faults on different lines, and with several fault parameters varied. This way, user can easily generate several test cases without even knowing the ATP input data format.

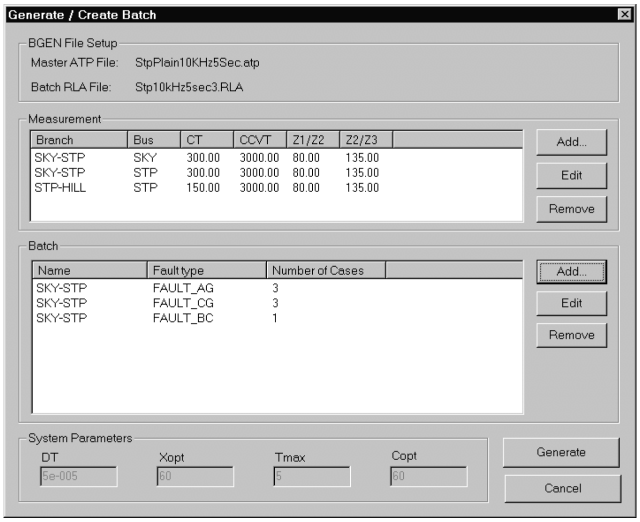

Fig. 6. BGEN: Specifying relay measurements and batch of test cases

After the user defines the batch of possible faults, BGEN automatically generates ATP input files, performs ATP simulations, and converts the simulation results into COMTRADE format [13]. In addition, it creates a test session file. Each test can be automatically repeated several times, which allows a statistical approach to testing.

VII. Conclusions

Based on the discussion, the following conclusions can be outlined:

- Transient testing allows "discovery" of important relay performance features for a given application
- Generating and applying fault transients in an automated way is an essential requirement when performing transient testing
- The hardware and software tools have to be carefully selected to make the transient testing efficient and cost-effective
- The hardware for transient testing has to be flexible allowing high accuracy and sufficient output power when replaying the transients
- The software for replaying recorded transients has to have a number of waveform editing functions to enable preparation of proper test waveforms
- The software for generating and replaying simulated transients has to provide automated means for dealing with large number of fault conditions

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IX. 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.

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