ADVANCED TOOLS FOR EVALUATION OF PROTECTIVE RELAY OPERATION

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Abstract – This paper focuses on specification requirements for new tools for protective relay evaluation that are desirable and expected to become widely available soon. The intended use of the tools for extensive evaluation of protective relays is discussed in the paper. The major benefits are defined emphasizing the features of the new tools and related capabilities in evaluating the relays.

Keywords: Protection, Simulators, Fault Recorders

1. INTRODUCTION

The protection of power systems represents a vital part of the overall control strategy aimed at providing a safe and reliable production, transmission and consumption of electric power. With further focus on improving the efficiency of operation of power systems while maintaining the reliability, it appears that the protective relay operation is going to be further scrutinized for its performance and held to even higher performance standards in the future. As a result the ability to test and evaluate protective relays to a greater extent than what was done ever before is expected. In response to the demand, new tools aimed at providing more comprehensive evaluation of protective relays are being introduced [1,2].

This paper focuses on specification requirements for some new hardware and software tools that have recently been developed as a result of extensive research activity undertaken by Texas A&M University and its industry sponsors. These tools fall into four basic categories: digital simulators [3], expert systems for automated fault analysis [4], simulation environments for evaluation of protective relay models [5], and devices for field measurement of instrument transformer transient response [6]. Since the details of the design and related implementation background for each of the developments have been widely published in the literature before, the discussion will concentrate on the silent features of the tools that are used to achieve some new benefits not readily achievable when using the existing tools in evaluating the protective relay performance.

The first section of the paper is aimed at setting the stage by indicating what are the protective relaying performance evaluation areas where some future improvements are needed and expected. The next four sections are devoted to presenting the features of the new tools and related benefits achieved by using those features in evaluation performance of protective relays. The mentioned features are outlined as specification requirements for future developments in this area. Future trends, conclusions and references are given at the end.

2. NEW EXPECTATIONS AND POSSIBILITIES IN EVALUATING PROTECTIVE RELAYS

The existing practice in protective relay evaluation is confined to the use of advanced computerized portable test sets. The protective relay vendors may use more elaborate digital simulator tools, but those tools are still pretty expensive and may not be affordable for most of the utilities. When the existing practice is analyzed for the purpose of defining further improvements, the following desirable features may be identified:

- Fully automated and comprehensive measurement of the dynamic behavior of the relay operating characteristic
- Efficient evaluation of the relay application using simulated and field data

<u>Understanding the dynamic behavior of the relay operating characteristic</u> is extremely important for verifying the soundness of the relay design and its appropriateness for given applications. Examples of the critical dynamic behavior are the expanding operating characteristic of a distance relay and its influence on the relay performance for variety of autoreclosing schemes and ground faults involving high values of fault resistance [7]. It may be argued that the tools for evaluating the relay performance for those features/conditions are readily available. This paper does not have an intent to further argue this point. However to keep the specification requirements clear, a summary of the expected testing conditions and features that need to be supported by the existing test sets aimed at measuring the operating characteristic is outlined in Table I. The selected test tools and their features need to be evaluated against the requirements stated in Table I to assess the level of automation and user support provided before a decision is made by the utility if the test tools meet the new expectations and possibilities in evaluating protective relays.

The use of the simulated and field data is not as common and as widely used approach in evaluating relays today. This approach is aimed primarily at evaluating relay performances

Table I. Advanced Test Set Features and Their Use in Comprehensive Evaluation of Protective Relays

Testing Feature	Related Benefits
Generation of voltage and current phasors for the following conditions: • Pre-fault i and v equal to zero • Pre-fault I = 0, and v = rated value • Pre-fault i and v exist	Provides for precise evaluation of expanding properties of the operating characteristic which may have profound impact on the relay performance under some fault and system operating conditions.
"Smooth" transition between prefault, fault and postfault phasors obtained by computing phasors using simple power system model.	Avoids artificial transitions in the i and v phasors and allows for assessment of the relay performance under dynamic changes in the test signals/systems.
Computation of appropriate i and v phasors for each type of fault and other fault parameters to be able to measure the trip points around each operating characteristic.	Enables measurement of a variety of operating characteristics of a given relay which allows evaluation of polarizing schemes, directionality, blocking of power swings, coverage of fault resistance, etc.
Fully automated determination of phasors, execution of tests, and assessment of operating characteristic once the relay is selected and theoretical operating characteristic properties are determined.	Allows for extensive phasor testing due to the automation and generates easy to understand report for rather complex phasor testing process.

for a variety of applications. In order to provide an assurance of correct operation under actual fault transients the vendors are testing new designs for some elected number of typical application conditions. As an example, for distance relays the following application conditions are taken into account: mutual coupling between parallel lines, slowly decaying dc offset, high frequency transients, saturation of current transformers, "ringing" of capacitor coupling voltage transformers (CCVTs) under a voltage collapse, protection of series compensated lines, etc. In order to perform such tests the vendors are using advanced analog, hybrid or digital simulators as well as extensive engineering and application expertise of its staff. The utility industry has not been performing such evaluations in the past due to the lack of testing tools that are affordable and easy to use. Lately, a number of new and affordable tools are developed that can significantly help operators in performing application tests using simulated and field data. A set of desirable features and related benefits for the new tools is identified and discussed in Table II. Should the advanced tools provide the features mentioned in Table II, it is expected that the utilities will be able to embrace the opportunity to evaluate the relay performance further. The main reason and hence the justification for this additional evaluation by the users is the fact that their applications may be quite unique and relay performance under very specific conditions needs to be verified [8]. Typical scenario of the need for such evaluation is the comparative assessment of multiple relay designs when deciding on a purchase of a new relay, or troubleshooting of relay misoperation.

Table II. New Features of Advanced Test Equipment and Their Use in Evaluating Relay Applications

Testing Feature	Related Benefits
Testing relays using simulated waveforms produced by ATP/EMTP [8] simulations.	Allows extensive relay evaluation for variety of fault and operating conditions due to the modeling and simulation capabilities of ATP/EMTP.
Testing relays using field recorded waveforms captured by Digital Fault Recorders [9].	Provides for evaluation of the protective relay operation for very specific waveforms recorded in the field which may be quite useful for troubleshooting relay misoperations.
Testing relay models instead of actual relays using very detailed relay modeling [10].	Enables extensive pre-evaluation of relay features for a variety of fault and operating conditions which may facilitate selecting relays for further detailed evaluation through testing actual relays.
Testing relays or relay models using detailed representation of instrument transformers based on field measurements of the time and frequency [11,12].	Extends the detail of the relay evaluation to studying the influence of instrument transformer behavior which may be extremely important in some very specific fault and operating circumstances.
Automating the testing process and test result reporting for the cases when large number of application tests is to be performed [8].	Makes the application testing practical and affordable which enhances the prospect of using this type of testing in the utility environments.

The next section of this paper discusses some specific developments of new testing tools that are aimed at meeting the user requirements indicated in Table II.

3. DIGITAL SIMULATORS

A variety of digital simulators have been developed recently using a number of different implementation approaches [13].

Table III. Specification of New Software Tools for Relay Evaluation - Digital Simulator Implementation

New Tools	Related Benefits
Simplified and easy creation of data for faults on transmission lines or power transformers.	Ability to produce ATP/ EMTP fault models without being intimately familiar with the auxiliary routines for producing the model parameters.
Automated equivalencing of power system at selected buses.	Possibility of creating power system equivalents to reduce the size of the simulated system.
Batch processing of fault simulations and creation of fault waveforms.	Capability of automating otherwise a lengthy process of simulating faults for different fault conditions such as type, location, incidence angle and fault resistance.
Batch processing of test files and automated creating of test reports.	Availability of an automated relay testing mode where large number of tests may be performed without operator's involvement.
Graphical representation of test results and related test waveforms.	Ability to view the test conditions and results in the X-R plane allowing for better understanding of the relay performance under test.
Signal processing and editing of waveform files before the tests are performed.	Capability to alter waveforms and other test conditions facilitating a sensitivity study of the relay performance.
Importing of variety of test files prepared in different ATP/EMTP formats.	Possibility of using the test waveforms created by others using variety of ATP/EMTP programs and different DFRs.

The background of the developments in this area undertaken by TAMU is widely published as well [3,14].

Among some recognized benefits of the digital simulator technology when used for relay evaluation are the following:

- Great flexibility and accuracy in representing the fault and operation conditions;
- Ability to automate the testing process for large number of tests;
- Capability of testing multiple relays simultaneously;
- Opportunity to evaluate relays for a variety of dynamic interactions between the relay and power system.

In order to utilize the mentioned benefits, the simulator software needs to incorporate adequate tools. It is interesting to note that the existing simulators have an extensive software support for relay testing but some of the much needed tools are not readily available. A specification of the desirable tools and related benefits is given in Table III. Detailed description of TAMU's contribution to development of some of these tools is given in the literature [14-16].

4. EXPERT SYSTEMS FOR AUTOMATED FAULTS ANALYSIS

This technology has been invented some time ago and its uses are becoming widely known today [17]. It has been previously used for analysis of data recorded by DFRs. TAMU's developments in this area have been known and are now commercially applied [18]. Some of the recognized benefits of this technology for relay evaluation purposes may be stated as follows:

- Automated determination of actual fault inception time;
- Automated determination of fault type and fault location;
- Automated determination of the sequence of events associated with operation of relays, communication channels and circuit breakers.

Automated analysis and comparison of operating times to determine differences between actual and expected operating times.

Based on the mentioned benefits, one can formulate specification for the new testing tools that can have the corresponding features directly applied to the relay testing process. A list of such specifications for the tools and description of related benefits is given in Table IV.

Table IV. Specification of New Software Tools for Relay Evaluation - Expert System Applications

New Tools	Related Benefits
Creation of an analysis report (see Fig.1) for DFR files to be utilized for relay testing.	Enables test operators to assess the information provided in the DFR file quickly allowing them to specify appropriate test cases efficiently.
Confirmation of the digital simulator outputs	Provides for a check of the simulator outputs by performing automated analysis of the outputs recorded by DFR and comparing the results with the test scenarios that were used to provide those outputs.
Creation of an analysis report for relays being tested	Performs analysis of the relay responses and related circuit breaker operations allowing automated creation of test reports and assessment of the results.

5. SIMULATION ENVIRONMENTS USING RELAY MODELS

Using relay models instead of actual relays is a well-known concept in relay testing and evaluating. This concept has been widely used in popular short-circuit programs such as CAPE and ASPEN. In those programs the relay models are phasor-based and relay measurement and operating principles are modeled using phasor-based equations.

New approach to relay modeling is to use transient-based models that represent accurately the relay response during fault transients. Such an approach is becoming more of interest as the information required to develop accurate transient-based models is being released by the vendors [10]. TAMU has reported some initial result in this area some time ago and it is now pursuing an elaborate development effort in this area as a part of an NSF and EPRI funded project [5,19]. Based on the mentioned developments, the following are some recognized benefits of this approach:

- Detailed evaluation of the relaying principle without needing to get the measurements from the internal logic of the relay.
- Detailed evaluation of the relay performance without needing to have physical relays tested.
- Detailed evaluation of the relaying schemes involving multiple relays without needing to have physical relays and communication channels connected together and tested.

EXPERT SYSTEM STATION REPORT

Date\Time Stamp of Event: 04/04/95, 12:44:44.938
Event number: 017 Sample rate: 5.99 [kHz]
Machine name: S.T.P. Serial number: 20299
Number of pretrigger samples: 1198 (12.0 cycles)
Total number of samples: 2926 (29.3 cycles)
Size of the event in tracks: 10 (320Kb)

EVENT DESCRIPTION

D. Velasco Ckt #27 is 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 this substation.

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 **0.0605 sec. [3.63 cycles]**.
The bus 52B contacts operate at **0.0537 sec. [3.2202 cycles]**.
The bus breaker status change after trip is applied is **1.2** [cyc].
The middle breaker status change after trip is applied is **1.6** [cyc].

LINE CURRENTS AND VOLTAGES

	Prefault	Fault	Postfault	
I0	0.0087	**24.19**	0.001	[kA]
Ia	0.2076	0.801	0.000	[kA]
Ib	0.1868	**22.83**	0.000	[kA]
Ic	0.1672	0.272	0.004	[kA]
V0	0.0008	**0.086**	0.001	[kV]
Va	283.70	272.6	282.2	[kV]
Vb	283.90	**106.4**	282.8	[kV]
Vc	284.70	272.7	283.6	[kV]
Vab	491.20	**327.6**	488.8	[kV]
Vbc	493.10	**342.6**	491.5	[kV]
Vca	492.05	483.5	489.4	[kV]

All above values are peak values.

Figure 1. Typical report obtained from an Expert System by automated processing of DFR Data.

Obviously, this approach requires detailed and accurate models of the relay components and system solutions. This information is not typically known to the user but vendors have full knowledge and can provide detailed models. It is expected that in the near future these models will be made available since the users may request them as a part of the bidding requirements when purchasing new relays.

Once the relay models are readily available, several testing tools may be developed to facilitate relay testing using these models. A specification of the desirable tools and their benefits is shown in Table V.

Table V. Specification of New Software Tools for Relay Evaluation – Use of Relay Models

New Tools	Related Benefits
Library of models of relay components for a given relay design	Allows the user to select any component model and evaluate its performance.
Library of models of complete relays corresponding to a given commercial product	Enables the user to extensively evaluate relays based on the models using a large number of test cases since the execution of the tests is far shorter then when the physical relays are used.
Library of models of complete relaying schemes corresponding to various options used in practice	Provides the user with an ability to evaluate a variety of possible relaying schemes without performing measurements in a physical system.
Simulation case builder for connecting various models of relaying elements, relays and schemes with test signal sources	Allows for the flexibility when evaluating variety of relay and system design and applications.
Auxiliary simulation environment support tools for connecting the measurement, result logging and result analysis tools to the relay modeling and simulation environment	Enables efficient monitoring of the relay evaluation process.

6. FIELD MEASUREMENTS OF INSTRUMENT TRANSFORMER TRANSIENT RESPONSES

The instrument transformer transient response may play a significant role under certain relay evaluation conditions. As an example, "ringing" of the computer coupling voltage transformer is quite prominent when the voltage collapses due to a fault. This phenomena has been extensively studied by TAMU using elaborate models for representing stray capacitances of CCVTs [6]. It was concluded that CCVT parameters may play a major role in determining the transient response. As a result, a device for field measurement of the parameters was demonstrated [20].

As a result of these studies, the following benefits were recognized:

- Detailed evaluation of the relays would be more comprehensive if the study included the relay behavior under instrument transfer transients.
- The instrument transformer designs for CCVTs are quite different and correspondingly their transient response characteristics are different which leads, to the need of measuring their characteristics.
- The difference in the designs affects the filtering characteristics of instrument transformers which requires detailed modeling of the transformer.

Having in mind the mentioned benefits, a number of specifications for a new update of the evaluation tools can be outlined. A list of desirable tools and their benefits is shown in Table VI.

Table VI. Specification of New Software Tools for Relay Evaluation – Use of IT Models and Field Data

New Tools	Expected Benefits
Library of instrument transformer models	Allows the user to utilitize these models in various relay evaluation scenarios.
Data acquisition software for field measurements of transient responses of instrument transformer (CCVT)	Enables the user to determine the transient response for a given fiel unit (CCVT).
Data analysis and diagnostics software for verification of CCVT response degradations.	Provides the user with an ability to determine if the field unit is healthy by analyzing the transient response characteristic.

7. FUTURE TRENDS

The future trends in developing new tools for relay evaluation and testing can be summarize as follows:

- Extensive utilization of the modeling and simulation technology
- Incorporation of advanced technologies for automated analysis of relay operation
- Implementation of data acquisition technology for assessment and use of field recordings.

As a result, future specifications for the new relay evaluation and testing tools may be represented with the following functional diagram shown in Figure 2.

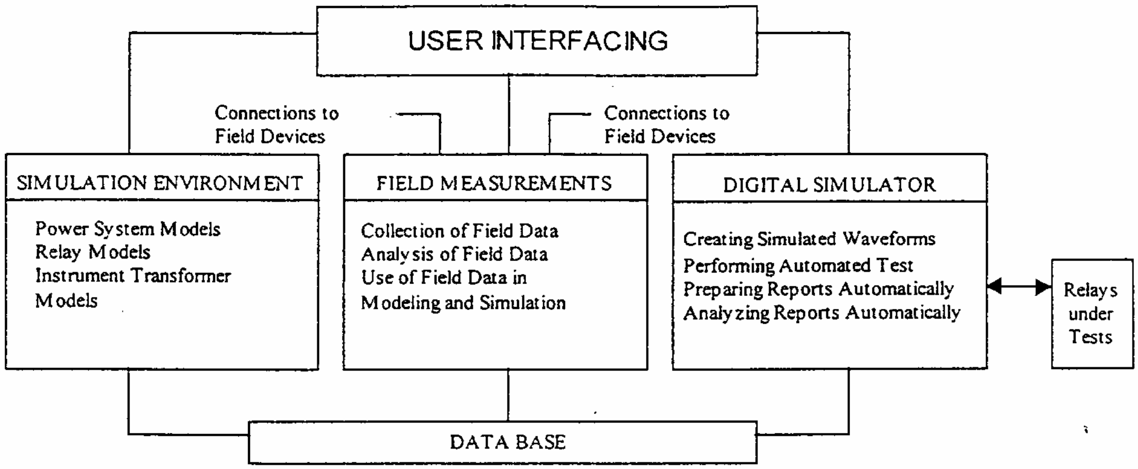

Figure 2. Functional specification of the future software for relay testing and evaluation.

8. CONCLUSIONS

Based on the specifications discussed in this paper, the following may be concluded:

- The technology for enhancing the relay evaluation tools is readily available and has already been demonstrated as being very beneficial.
- Implementation of the specified features is required if advanced relay evaluation tools are to be widely used in the future.
- The existing relay evaluation and testing tools are quite useful but do not allow for full utilization of possible capabilities.
- The relay evaluation and testing in the future may be made more detailed and precise allowing for further improvements in the performance and reliability of protective relays and relaying systems.

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