New Test Methodology for Evaluating Protective Relay Security and Dependability

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***Abstract*--This paper presents a new test methodology for evaluating the security and dependability of protective relay operations. A discussion of the important impact of relay security and dependability on power system reliability especially during cascading events and unusual operating conditions is presented. The new test methodology includes comprehensive power network modeling, generating test scenarios and automating simulation. The digital simulator based protective relay test setup used for the application of physical relay testing is described. Three distance relays are tested using the proposed methodology. The test tools utilized and results obtained are outlined at the end.**

***Index Terms*—protective relay, test methodology, relay security, relay dependability, cascading events**

I. Introduction

RELAY plays an important role in protection of power system. It is designed to detect fault and make decision locally to isolate faulted power system parts from the rest of the system. The correct operation of protective relay can clear the fault, as well as reduce and/or eliminate the impact of disturbances on power system. On the contrary, unintended or incorrect operation may further deteriorate the system condition and even jeopardize the stability of the entire system [1]. Final report on the August 14, 2003 blackout indicates that a number of protective relays have not operated as intended. It also indicates that many key transmission lines were incorrectly tripped one after the other by zone 3 distance relays, which resulted in an overload rather than faults causing subsequent cascading outages. Additionally, the reason might have been that the performance of the relays was different from what was specified in the manufacture's manuals for different power system operating conditions.

Appropriate relay testing should help validate the design of the relay logic, compare the performance of different relays, verify selection of relay settings, identify vulnerable conditions apt to causing unintended operations, and carry out post-event analysis for the understanding of unintended or incorrect relay behavior. The challenge of test and evaluation tasks and related methodology lies in implementation of large number of test and evaluation cases. This requires methods for accurately modeling the power system used for tests, easily simulating disturbances, facilitating interfacing relays and power system models, and automatically executing batch tests and collecting relay response events. The various approaches related to the software programs for modeling protective relays and power systems, which are used to study relaying algorithm and characteristics are explored before [2]-[4]. Test equipment is developed to interface test data with physical relays [5], [6]. The test methodology based on phasors for evaluating design characteristics of a relay is also implemented [7]. Extensive study and development of new test methodology and test tools has been done at Texas A&M University over the years. The solution interfacing digital protective relay model and power network model allows a real time simulation environment [8]. Since the protective relays are modeled with advanced programming language, it is easy to implement the simulation for the relaying algorithm performance study [9]. This solution can also be used as a pre-study tool for selecting specific scenarios of interest so that the unnecessary relay test trails are avoided. Advanced digital simulators are utilized to implement comprehensive application tests on physical relays [10].

Although a number of test methods and tools for relay tests have been developed in the past, they did not specifically focus on the issues how to select appropriate power system model and test scenarios for comprehensive evaluation of relay design features and performance characteristics affecting security and dependability of protective relay operation. This paper follows the conclusions and recommendations from the Final Report of the August 14, 2003 blackout, which illustrates the existing problems of applying distance relays, and emphasizes the importance of relay security and dependability. A new test methodology for evaluating protective relay operation using transients is proposed. Two types of relay test are defined according to the different test objectives: conformance test and compliance test. Power network models used to simulate disturbance scenarios are addressed including the models formed with the Alternative Transients Program (ATP). The method how to select test scenarios corresponding to test types is described. Test scenarios are generated in an automated way through simulation. The idea of forming the test cases library for protective relay tests is proposed as well. This library includes

The work reported in this paper is funded by NSF I/UCRC called Power Systems Engineering Research Center (PSERC) under the Project T-30 titled "Transient Testing of Protective Relays: Study of Benefits and Methodology".

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test scenarios generated from the simulation, digital fault recorder (DFR) records and blackout scenarios of interest. It can be widely utilized as a reference for evaluating security and dependability of protective relays. A laboratory setup for such relay tests is developed. Three distance relays are selected for the implementation of tests using the new test methodology proposed in this paper. Test results and conclusion are outlined at the end.

II. Discussion of Situation When Relays Failed to Offer Discriminative Security and Dependability

Dependability is a measure of the capability of a protective relay system to operate correctly when required. Security is a measure of the ability of protective relay system to not operate incorrectly [11], [12]. These two factors are usually used as criteria for evaluating the effectiveness of the relaying system applied to power system.

An ideal relay is expected to provide fully discriminative dependability and security. The non-operation of the relays when there is a fault may result in destruction of power system components and the collapse (blackout) of the power system. The incorrect operation may also reduce the overall service survivability of the power system. A review of major system disturbances, such as blackouts, indicates that a fatal consequence of a disturbance is more likely to be caused by an unintended operation of a protective relay rather than the non-action [1]. An unwanted trip may occur on a line that does not have a fault, which may be caused by a relay that operates due to short term increase in load caused by the opening of another line in the system. This may be a result of the relay design or application flaw.

The Final Report of the August 14, 2003 blackout concludes that the unwanted operation of zone 3 distance relays took place due to the low voltage and high current condition, which triggered the cascading outage. Since the unwanted operation could have not been corrected by either operator action or automatic means, there really was not much that could have been done on-line that could have limited or mitigated the unfolding cascade. The report gives a recommendation for evaluating the settings of zone 3 distance relays so that the security of the power system may be improved [1]. This paper addresses the test methodology aimed at facilitating the relay evaluation.

The security and dependability features of a protective relay may be affected by several factors such as the relay system design scheme relay operating characteristic, setting coordination, application conditions, etc. These two features can be evaluated through the application of appropriate relay tests. Before a relay is applied to a specific power system, the relay performance should be fully evaluated to satisfy the protection requirement. If there are conditions apt to causing unwanted operations, some additional control and/or protection schemes should be considered to ensure continuity of the security of the power system operation.

III. New Test Methodology

The new test methodology is discussed with emphasis on the test classification, test scenario selection, power system model used for fault simulations and the test case library. This test methodology is based on the transient signals [13], [14] which are close to the reality and provide more accurate results than that of traditional based methods [15]. The implementation of the test methodology on the three selected distance relay products is presented in section IV.

A. *Test Classification and Scenario Selection*

According to the test objectives two different types of tests are defined: conformance test and compliance test. Both types of tests are performed by using transient waveforms.

1) *Conformance Test*

The objective of conformance test is to evaluate relay design functionality and operating characteristic, and to verify relay settings, which is achieved through implementation of comprehensive series of tests. The concern of this test is the statistical performance related to the relay operating characteristic and tripping time.

To fulfill this test, a batch of test cases with a variety of disturbance conditions including faults and non-faults are generated through simulation as given in Table I.

TABLE I
TEST SCENARIOS FOR DESIGN TEST

Fault Conditions	Non-Fault Conditions
Internal fault	Line closing
External fault	Loss of potential
One-end-open internal fault	Loss of load
Switching onto fault	Restoring potential
Fault during power swing	Power swing
Fault during frequency fluctuation	Load encroachment

When a protective relay is selected for application in a power system, its operating features and settings should be evaluated to meet the basic protection requirement for the power system. This can be achieved through executing conformance test on the target relays. However, the application problems which may cause relay unwanted operation (security problem) and/or lack of operation (dependability problem) due to some vulnerable transmission line loading cases and unusual overall power system operating conditions may still go undetected, even though the equipped relaying system was properly tested verifying that operating characteristic and settings are correct. These unexpected problems could be detected by applying compliance test.

2) *Compliance Test*

The objective of compliance application test is to verify whether a relay can operate correctly under peculiar circumstances in power system particularly during abnormal operating conditions. That is to say, this type of test is to investigate the compliance feature that “real” performance of a protective relay complies with its expected performance. The concern of this test is the trip/no trip response and relay operating time performance under specific scenarios. The first task for the application of compliance test is to select those possible scenarios which may cause relay unintended operation. Two approaches named steady state approach and dynamic state approach are proposed to achieve this task.

The steady state approach uses the steady state methods to find some transmission lines that are designated as vulnerable lines due to stressed power system operating conditions creating major overloads. Those important lines must have high security level of the protection scheme. For a given system, topology processing method [16], [17] will find important lines, such as tie-lines, or single-connection lines whose outage will disconnect the generator, load or even part of an area, parallel lines, long lines, etc. Power flow method is used to identify transmission lines witch may have overload conditions and whose connected buses may have low voltage problems. Under such conditions, the apparent impedance seen by distance relays may fall into their backup protection zones. They may trip the lines and trigger the cascading outage.

The dynamic state approach studies the protective relays in dynamic conditions such as the case when after the fault and its clearing, the power swing occurs, which may confuse some distance relays as the apparent impedance may fall into the protection zones. The relays may operate as not intended and cause conditions that may result in further tripping. The dynamic apparent impedance phasors can be retrieved from the time domain transient stability analysis and such waveforms are evaluated to select the power system scenarios of interest for the application relay tests [18].

B. Power System Model Used for Disturbance Simulation

A reference model created by IEEE Power Engineering Society's Power System Relaying Committee (PSRC) is used for the conformance test [19]. Fig.1 shows the one-line diagram of the reference model. The ATP model used for generating disturbance scenarios is also given in Fig.2 [20].

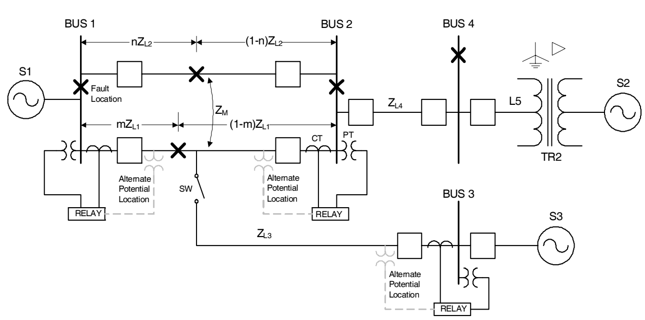

Fig. 1. One line diagram for IEEE PSRC system

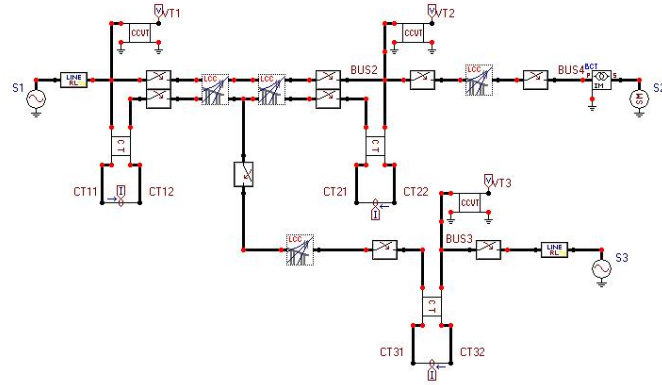

Fig. 2. ATP model for IEEE PSRC system

The study of selecting vulnerable conditions for the compliance test is achieved by using the IEEE 14-bus system [21]. It has 5 synchronous machines, 20 branches, 11 constant impedance loads, as shown in Fig.3. Various disturbances can be simulated on the ATP model given in Fig.4.

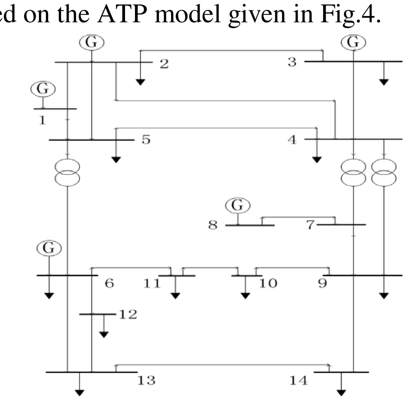

Fig. 3. One line diagram for IEEE 14-bus system

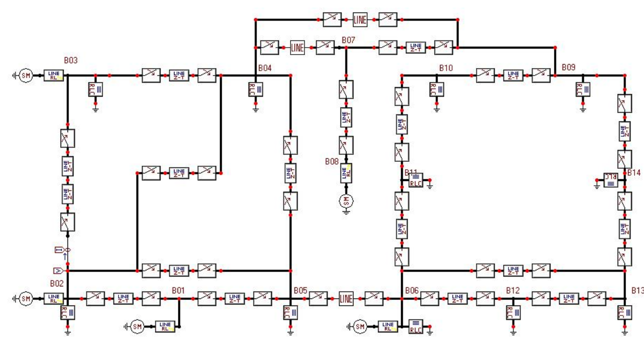

Fig. 4. ATP model for IEEE 14-bus system

C. Test Scenarios Generation

A batch simulation program used for automatically generating disturbance scenarios is developed in MATLAB [22]. The block diagram for this program is given in Fig.5. It can automatically simulate fault scenarios with different fault types, locations, inception angles and fault resistances according to the pre-set conditions. The output format of waveforms can be PL4, MAT and COMTRADE, which can be used for multi- purpose study and analysis [23]. The manual simulation for studying specific scenarios, such as power swing, load encroachment, etc, can be implemented on

ATP models as shown in Fig.2 and 4.

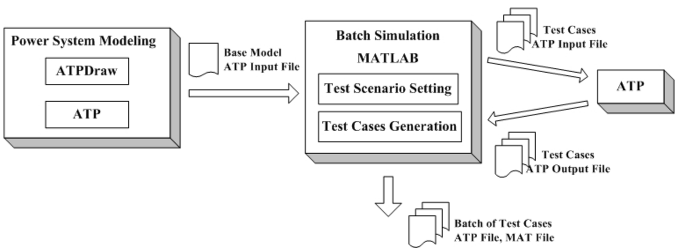

Fig. 5. Block diagram for batch simulation program

D. *Test Case Library*

For each of the relay types considered, a library of power system models and disturbance scenarios is created. As shown in Fig. 6, the test scenarios generated for the application of conformance test and compliance test are selected into the library. The abnormal power system operating conditions and vulnerable transmission lines which may cause relay unintended operations can also be built into the library. The scenarios of interest from digital fault recorder (DFR) records and blackout events can be added to the library as well. The test case library can be used widely as a reference of test cases for relay performance evaluation and trouble shooting.

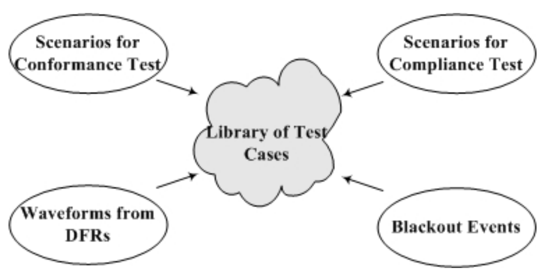

Fig. 6. The library of relay test cases

IV. Test Implementation Using New Methodology

The section presents the test setup and test procedure for the implementation of relay tests using the new methodology. Three distance relays are selected for the study and test results are given as well.

A. *Test Setup*

The lab setup is shown in Fig.7. The major components include a PC used to run related software programs, a digital simulator used to generate "real" voltage and current signals and the physical relay under test. A commercial software program called Relay Assistant residing on the PC communicates with digital simulator is capable of sending transient voltage and current data and receiving contact status data [24]. The digital simulator applies the voltage and current waveforms to the relay and records the relay trip contact status. A relay setting software program residing on the PC communicates with the relay to configure relay settings and an automated relay file retrieval software program residing on the PC communicates to the relay to automatically retrieve relay event reports triggered by certain pre-set conditions.

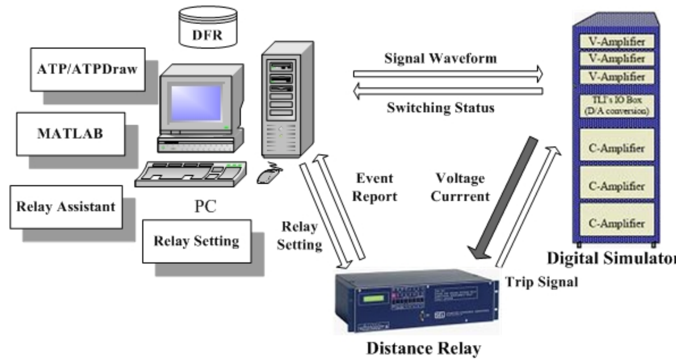

Fig. 7. Lab setup for physical relay test

B. *Test Procedure*

The implementation of protective relay test can be presented using Fig.8. The test procedure is described as follows:

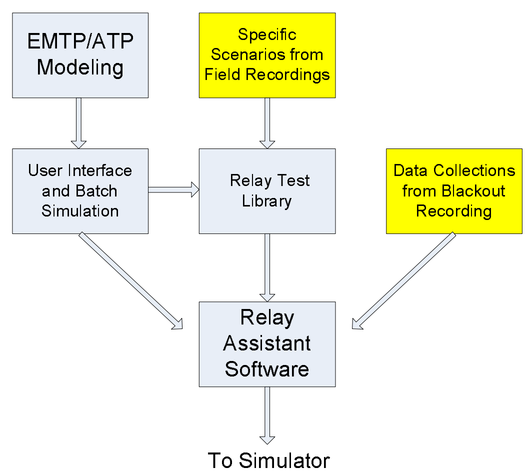

Fig.8. Framework of implementation for relay test

(1) Generate test cases. The ATP model of power network and batch simulation program are used to generate test cases which contain transient voltage and current waveforms related to various disturbance scenarios. The cases of interest from DFR and blackout recordings are selected for the tests.

(2) Convert Data format. A program developed in C++ is used to automatically convert various formats of test cases to the format which can be recognized by Relay Assistant software, such as COMTRADE.

(3) Create test session. The test session is created by loading selected test cases with Relay Assistant software. Each test session contains specific scenarios sorted by different types of disturbances or power system operating conditions. For example, the fault session can be sorted with fault type, location, inception angle and resistance. A loaded test case is given as an example in Fig.9.

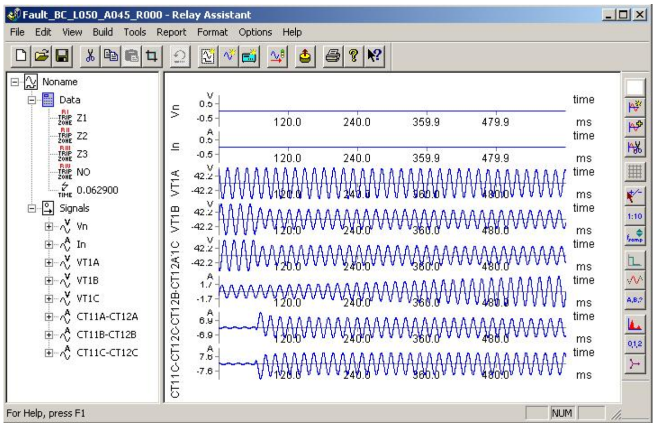

Fig.9. An example of test case displayed in Relay Assistant software

(4) Set protective relays. The relay settings group corresponding to a given transmission line and protection scheme is activated from the relay front-panel buttons or through the relay setting program.

(5) Execute test and retrieve report. The "real" voltage and current signals generated by simulator are sent to the relay. The relay responds to the input signals for each case and generates an event report containing the detailed operation information. The trip signals are captured by simulator as output signals and used to automatically calculate the initial operation feature such as tripping time. The event reports are collected by the retrieval program for further study.

C. *Test Results*

Three different distance relays are selected to implement relay test using proposed methodology. They are applied in the IEEE PSRC system model to protect one of the parallel transmission lines between bus 1 and bus 2, as shown in Fig.10.

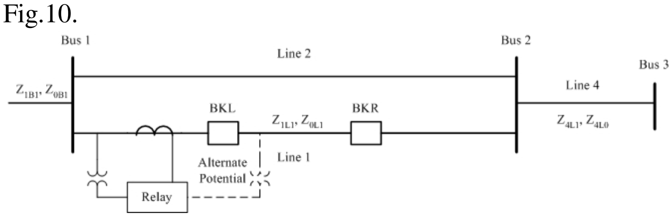

Fig. 10. Relay application in PSRC system model

The IEEE PSRC reference model from Figure 10 and IEEE 14-bus system model , which are described in detail in [19], [21] are utilized for the conformance test and compliance test respectively. The three distance relays selected for the test implementation are set with various protection functions typically used in the field. The settings are calculated based on the power system parameters used in the models and referred to in the manuals provided by vendors. Some adjustments of setting values are made for the various test purposes such as protection functionality, settings calibration, dynamic performance etc. The modularity and flexibility of the proposed test environment enable users to customize the tests including power system models, test scenarios, test procedures and test setup,

An example of results obtained by executing conformance test on one relay is given in Table II. In this example, different test cases were simulated for different type of faults, locations, and inception angles. Each test is repeated 30 times, and statistical methods are used for determining operating time for tested relay [25]. One can notice very interesting results with respect to differences in operating times for different fault conditions as well as differences between maximal and minimal values of operating time for the same fault condition.

TABLE II
EXAMPLE OF STATISTICAL TEST RESULTS

Type	Loc [%]	α [deg]	Trip Zone	No.T	MeanT [ms]	MaxT [ms]	MinT [ms]	Devtn [ms]
AG	50	0	I	30	22.57	24.30	20.60	0.85
AG	70	45	I	30	28.32	30.90	27.40	0.82
AG	90	90	II	30	318.20	357.1	313.4	7.87
BC	50	0	I	30	24.71	26.40	22.50	0.79
BC	70	45	I	30	28.64	30.30	26.80	0.83
BC	90	90	II	30	356.23	357.1	355.1	0.59
BCG	50	0	I	30	18.73	20.10	17.90	0.58
BCG	70	45	I	30	29.72	31.20	28.10	0.65
BCG	90	90	II	30	365.47	370.3	360.0	1.12
ABC	50	0	I	30	20.88	21.90	20.00	0.61
ABC	70	45	I	30	31.25	33.40	29.30	0.97
ABC	90	90	II	30	359.65	361.3	357.2	1.41

Another example of results obtained by applying conformance test is given in Fig.11. The figure depicts a comparative analysis of trip time vs. fault location for three distance relays. Trip time shown in the Fig.11 is obtained statistically after several tests cases are repeated. Relays are set to operate in zone 1 coving 80% of the line. An interesting outcome is that the trip time, for some relays, becomes much longer than expected.

These results provide the important information which was not documented in the relay manuals, and definitely may affect proper coordination of the relaying schemes.

The compliance test results show that some relays operated unintended by either over-reaching or under-reaching in some cases. The zone 3 relay performance is also tested. It is indicated that during some unusual power system operating conditions, particularly during power swing and heavy loading situations, zone 3 relays operated incorrectly by tripping unfaulted lines.

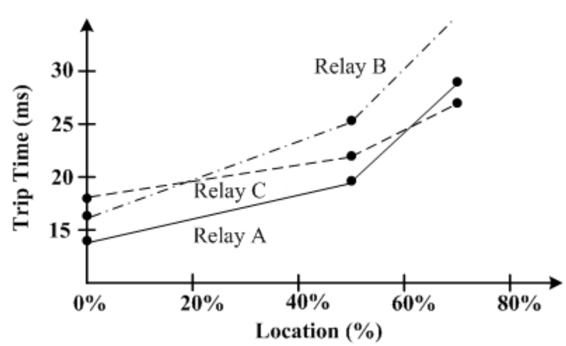

Fig. 11. Example of comparative test results

V. Conclusion

This paper presents a new test methodology for evaluating protective relay dependability and security. The important impact of relay dependability and security in power system is discussed. The unintended operation of protective relays may cause cascades when power system operates in abnormal conditions such as increasing heavy loads followed by multiple line trippings. Appropriate relay test can help evaluating relay performance and figuring out the vulnerable conditions apt to causing relay unwanted operation. The proposed test methodology includes the issues how to model power system used to generate disturbances and study specific conditions, how to select and generate test scenarios, and how to execute relay test in efficient way. An idea of forming a test case library for relay users so that the test scenarios can be used repeatedly as a reference is outlined. A test lab setup developed at Texas A&M University for physical relay tests is introduced. The test procedure of relay test implementation on the platform and the use in relay testing are also presented. Three different distance relays are selected to implement relay test using the proposed methodology and the tests results are given at the end. The proposed test methodology together with test tools and the test case library composes a comprehensive test environment for evaluating the dependability and security features of protective relays.

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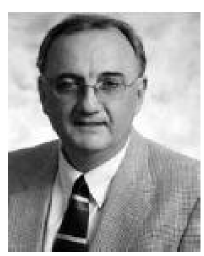
VII. Biographies



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Jinfeng Ren (S'07) received his B.S. degree from Xi'an Jiaotong University, Xi'an, China, in electrical engineering in 2004. He has been with Texas A&M University pursuing his Ph.D degree since Jan. 2007. His research interests are digital simulator and automated simulation method for protective relay testing and applications in power system control and protection.