Transient Based Relay Testing: A New Scope and Methodology

Nan Zhang, Hongbiao Song, and Mladen Kezunovic, *Fellow, IEEE*
Texas A&M University, Department of Electrical and Computer Engineering, College Station, Texas 77843-3128, USA
Emails: zhangnan@tamu.edu; songjefferson@tamu.edu; kezunov@ece.tamu.edu

Abstract— **This paper provides an overview of the scope and methodology for transient relay testing. The scope of transient relay testing is divided into: a) conformance test for examining the functionality and generic performance characteristics of relays, and b) application test for analyzing the specific performance issues and trouble-shooting relay misoperations. For conformance test, the methodology including system modeling, automated generation of test scenarios, relay modeling, and implementation of automated relay testing is discussed in detail. For application test, the key issue is the selection of typical scenarios for analyzing the relay behavior in vulnerable system conditions. A view about benefits and approaches of transient based relay testing is explained in this paper.**

I. Introduction

Relay testing is a very important issue when applying the protective relays. The vendors need an evaluation tool to validate the design of the relay logic. The utilities need an assessment tool to compare the performance of different relays, calibrate relay settings and carry out post-event trouble-shooting. The universities also need a simulation environment to investigate relay principles and develop new relay algorithms.

The methods using transient signals to implement relay testing [1], [2] are more accurate than the traditional phasor based methods [3], [4] because they use waveforms that are much closer to reality. Most of the transient testing solutions try to address the issue "How to implement transient based relay testing using available simulation tools?" [5]. That is actually the last step in implementing the methodology. For a much clearer view of the benefits of using transient based relay testing, we must extend the issue by asking the following question "What could be done with transient based relay testing?" For example, the final report of the August 14, 2003 blackout indicates that a number of protective relays have misoperated [6]. A common belief is that the misoperation was caused by wrong selection of settings. This kind of issue can be studied only using transient based relay testing since the traditional methods may not provide adequate level of detail. When the scope of transient based relay testing is determined, a new methodology to match that scope should be discussed. The implementation of relay testing is important, but the issues of selection of system model, generation of test scenarios, implementation of software simulation tool, etc., also need to be addressed. In the following sections, the new scope and methodology for testing distance relay using transients are discussed in detail.

II. Scope of Transient Testing

A. Conformance Test

The basic objective of conformance test is to verify functionality and generic performance characteristics specified by vendors for different kinds of relays.

The traditional phasor based test methods were used to implement those tasks. The input signals are ideal sinusoidal functions. By adjusting the magnitude and angle of the signals, the operating characteristic of relay is obtained and compared to the theoretical one or the one given by the vendor. This is a steady state method which can not represent an actual situation during the fault and is not enough to verify the security and dependability of a relay.

The relay behavior can be quite different during the transients. A previous study showed the variation of trip time between 15 and 80 milliseconds for the zone 1 direct trip among the five relays that saw the same fault cases [1]. Also, some relays misoperated by either over-reaching or under-reaching in some instances while other relays were operating selectively under all circumstances.

The conformance test using transient signals is very helpful in determining basic relay performance characteristics. A batch of fault and no-fault transient scenarios should be used. The performance indices consist of dependability, security, selectivity, operating time, etc. The statistical performance of phase selection and fault location can also be evaluated.

The methodology of the conformance tests is as follows:

- Select a "standard" power system model suitable for creating different test scenarios.
- Generate a reasonable set of test scenarios and form a scenario library for easy reuse.
- Automate the test procedure to minimize the test time.
- Implement comparative tests for a set of different relays with similar functions.

B. Application Test

The objective of application test is to verify whether a relay can operate correctly under certain circumstances in a particular system. After the basic relay characteristics evaluation is performed by the conformance test, the application test can be used for analyzing the very specific performance issues [2]. It can also be used for trouble-shooting of a specific relay operation. A simple example is diagnosis of the reason of the distance relay failing to trip a faulted transmission line or falsely tripping a healthy transmission line.

The evidence in the literature indicates that 70% of large area blackouts involve relay misoperations [7]. In this case, the relay operations and system stability are mutually related. As an example, a sequence of relay misoperations during the Aug 14, 2003 blackout is described as follows [6]:

"The Sammis-Star line tripped at 16:05:57 EDT on a zone 3 impedance relay although there were no faults occurring at the time, because increased real and reactive power flow caused the apparent impedance to be within the impedance circle (reach) of the relay. Between 16:06:01 and 16:10:38.6 EDT, thirteen more important 345 and 138-kV lines tripped on zone 3 operations that afternoon at the start of the cascade. These included several zone 2 relays in Michigan that had been set to operate like zone 3, overreaching the line by more than 200% with no intentional time delay for remote breaker failure protection. All of these relays operated according to their settings. In the full cascade phase, between 16:10:39 to 16:10:44 EDT, some zone 1 relays on the long 345-KV tie-lines with high impedances separated Pennsylvania from New York because the impedances fell into their zone which is due to the large power swings."

This kind of problem can be analyzed with the help of transient based relay testing. The approach can be divided into a preventive study and a post-event analysis. For the preventive study, the problem should be analyzed using a dynamic system model. Through a series of contingency analysis, one can find out several worst cases, and use transient testing to make sure the relay settings are appropriate for those scenarios. For the post-event analysis, the relay misoperation cases will be collected. By replaying the recorded fault waveforms to the relay, one can find out the problem and correct it to avoid similar events in the future.

III. Methodology for Conformance Test

A. Power System Modeling

In order to study the basic performance of a distance relay, a suitable power system model is needed. The model should be standardized so that the results of relay testing can be comparable for each type of relay. The existing practice is that all the vendors use their own test arrangement therefore the type of technical data in the relay manuals is dependent on the scenarios they generated. Recently, Power System Relaying Committee (PSRC) of the IEEE Power Engineering Society (PES) has developed a standard system model for relay testing, as shown in Fig. 1 [8]. This basic model is made up of different components such as lines, transformers, sources, CCVT, CT, etc. The model is capable of simulating mutually coupled line, three-terminal line, and various fault and no-fault scenarios by selecting different parameters.

Utilities also need to test the relay performance when different relays are applied in their own power system. In that case, the utility needs a model of their system for relay testing. The lines of interest can be represented in detail and other part of the system can be reduced to the boundary buses using Thevenin equivalent. Both of the mentioned power systems are implemented using an appropriate modeling and simulation tool. The most popular transient simulation tool is the Electromagnetic Transients Program (EMTP or ATP) [9].

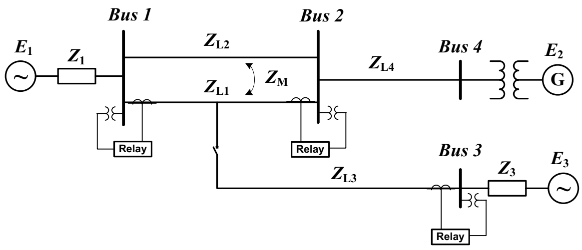

Fig. 1. IEEE reference system model

B. Test Scenarios

The conformance test usually requires a batch of test scenarios including a variety of fault parameters and system conditions. The existing EMTP/ATP software does not have the capability to automatically generate the scenarios in a batch. A routine for automatically generating test scenarios needs to be designed to avoid a tremendous manual work. A scheme is shown in Fig. 2. This scheme is designed to generate the batch scenarios conveniently. MATLAB [10] is used as a control tool to trigger the simulation in ATP with different scenarios.

For a given power system model, the graphic model (.adp) is built using ATPdraw and a template (.atp) file in the steady state is then generated and saved. The system configuration file (.txt) is used to indicate the name of system components. It is set by the users along with a scenario setup file (.txt) and read by the MATLAB routine. The MATLAB program will automatically sort out the entire scenario file, then modify the template file and trigger the ATP execution once at a time. After the ATP is executed, the transient measurements for each scenario are then stored and used for evaluation of relays or other fault analysis algorithms. The data format can be pl4, mat or COMTRADE [11] according to different uses. When

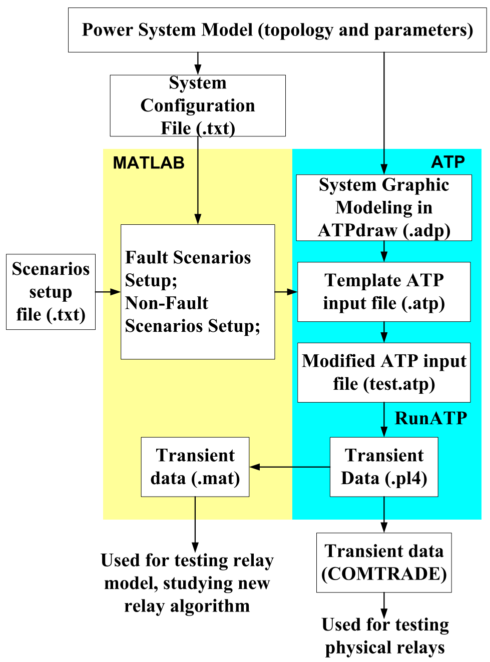

Fig. 2. The framework of power system modeling and scenarios generating

different power system model is used, we just need to change the ATP template file, system configuration file and scenarios setup file. The inside routine of the MATLAB program does not need to be changed.

Using the IEEE reference system model, we can generate a variety of different fault and no-fault scenarios as well as some special applications. Those scenarios can be formed as a comprehensive library of transient and dynamic tests to be used to evaluate the dependability, security, selectively and fault clearing time of different relays. The generated library cases can easily be used by different vendors and utilities for relay performance assessment.

C. Software-implemented Relay Model

The relay model is very useful during relay testing. It can be used as the pre-screening tool for selecting the useful scenarios for testing physical relays so that the unnecessary trials are avoided. It can also be used for pre-study of the specific performance issues of interest. Since there is no hardware involved, testing using relay models can easily be implemented using the batch simulation. Only the suspect cases will be sent to the physical environment to implement the final assessment.

At Texas A&M University, three types of relay models were developed. The first type is a SIMULINK based package, having a group of relay elements and other protection system components [12]. The second type is a distance relay model designed as a MATLAB routine. The third type is distance relay model embedded in EMTP/ATP and implemented using the EMTP/ATP MODELS language and C++ [13]. The first two kinds of relay models are suitable for the open-loop simulation. The one using SIMULINK has more relay elements and functions, as well as a good graphic interface to illustrate individual scenarios. The second one is suitable for batch simulation. It is also capable of showing the relay impedance trajectory when used for demonstrating a single test scenario. The third one, since it is embedded into the EMTP/ATP system model, can be used for close-loop simulation. The prominent advantages are the capability of implementing system/relay interactive simulation and the capability of simulating multiple relays in a system.

The accuracy of the software-implemented relay model can be verified by comparing simulation results from physical relays using a group of identical test scenarios. Once the model is calibrated to have a similar performance as the physical relay, it can be used as a pre-screening tool efficiently.

D. Implementation of Transient Tests

The procedure for implementing the transient relay tests is shown in Fig. 3. The previously mentioned simulation scenarios and field recordings are formed as the library of test cases. A laboratory setup for performing relay tests is shown in Fig. 4. The major equipment are PC, PC-based digital simulator [14] and physical relays. The PC-based digital simulator deployed at Texas A&M University is capable of testing several relays simultaneously. The signals exchanged between PC, digital simulator (amplifiers and D/A converters), and distance relay are marked in Fig. 4. The signal waveforms (voltage and current) from the library of test cases are sent to the digital simulator to obtain the "real" voltage and

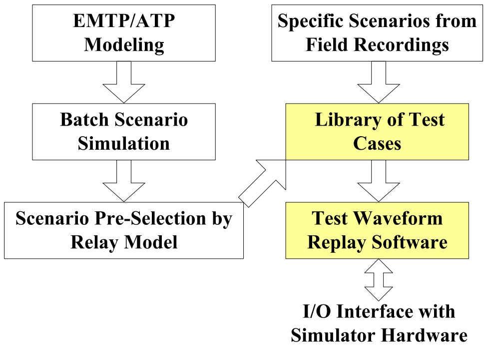

Fig. 3. Procedure for relay testing using transients

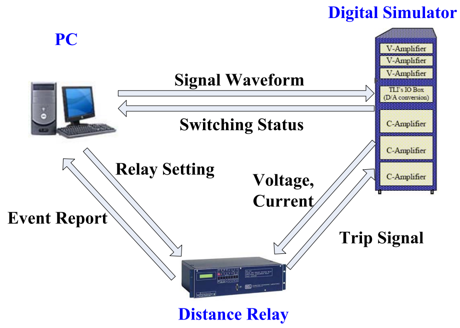

Fig. 4. Laboratory setup for relay testing

current for the relay input. The distance relay will respond to the waveforms and send trip signal to the simulator digital (contact) inputs if a fault is detected. The contact information is collected by the computer for the test result analysis.

IV. METHODOLOGY FOR APPLICATION TEST

The application test is used for analysis and trouble-shooting of the specific application issues. Implementation of this test is same as for the conformance test, which is shown in Fig. 4. The key issue is how to select useful scenarios for studying the relay behavior in a specific large scale dynamic system.

For a specific power system, there may be two reasons for studying protective relays to ensure the system security: one is to evaluate or replace the old transmission line relays [2]; another is to find vulnerable locations where relays may misoperate due to abnormal operating conditions. For the former case, the locations may already be known. Detailed simulation studies based on different fault and no-fault conditions during various operation conditions need to be performed to choose the proper relaying schemes. For the latter case, the vulnerable locations need to be found first. Then detailed simulation studies will be performed to test the relays. If the relays at those lines misoperate during the no-fault or external fault conditions, adjusting relay settings and communication schemes needs to be considered or better relaying scheme needs to be chosen.

A. Steady State Selection Approach

This approach uses steady state methods to find some important transmission lines or vulnerable lines due to stressed operation conditions. Those important or vulnerable transmission lines must have high security level of the protection scheme. Topology processing method and power flow method will be used to identify those lines [15], [16].

For a given system, topology processing method [15] 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 [16] will be used to identify transmission lines which may have overload conditions and whose connected buses may have low voltage problems. The apparent impedance seen by distance relays may fall into their backup protection zones. They may trip the lines and trigger the cascading outage. As described in Section II. B, the tripping of the Sammis-Star 345KV line during the August 14, 2003 blackout is one of these examples.

B. Dynamic Selection Approach

From the traditional transient stability analysis point of view, if the fault is cleared before the critical clearing time (CCT), the system will be stable. The CCT is the maximum tolerable tripping time. The basic assumption is that there are no other relay actions before and after this trip. After the disturbances, the power swing may occur, which may confuse distance relays as the apparent impedance falls into the protection zones. The relays may misoperate and initiate further tripping. Thus dynamic behavior of distance relay performance needs to be studied. The dynamic apparent impedance phasors can be retrieved from the time domain transient stability analysis [17].

C. Transient Testing Approach

The list of transmission lines from the steady state and dynamic selection are comprised of important lines and suspiciously vulnerable lines. For a large system, the number of relays that need to be carefully evaluated in detail will be greatly reduced by using this approach. With the help of relay model embedded in EMTP/ATP, we can further select a group of scenarios that could cause relay misoperations. The dynamic system model and relay model can be incorporated in EMTP/ATP. The EMTP/ATP relay model can be connected to the transmission line models from the list created by steady state and dynamic selection. We can obtain each relay actions through a set of contingency scenarios. If relay misoperation is found, that scenario will be recorded and saved into the library of test cases, which will be used for validating behavior of physical relays.

V. Conclusion

The transient based relay testing is a more accurate method to verify relay functionality than the traditional phasor based method. It can also be used for analyzing and trouble-shooting specific events where relay misoperated. The proposed method for system modeling and generating fault scenarios is helpful in building standard test cases library efficiently using different system models. The software-implemented relay model is very helpful for pre-selecting test scenarios. For application test, the steady state, dynamic and transient selection approaches effectively reduce the number of scenarios for analyzing relay behavior under different system contingencies.

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Biographies

Nan Zhang (S'04) has been with Texas A&M University pursuing his Ph.D. degree since Jun. 2002. His research interests are power system analysis, power system protection, power system stability, system-wide disturbances.

Hongbiao Song (S'04) has been with Texas A&M University pursuing his Ph.D. degree since Aug. 2002. His research interests are power system analysis, simulation, protection, stability and control.

Mladen Kezunovic (S'77, M'80, SM'85, F'99) 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 the IEEE.