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IMPROVING RELAY PERFORMANCE BY OFF-LINE AND ON-LINE EVALUATION

Mladen Kezunovic, Jinfeng Ren, Chengzong Pang
Texas A&M University
U.S.A
kezunov@ece.tamu.edu

ABSTRACT: Protective relays are designed to quickly and correctly clear the fault and minimize the impact of disturbances on power system. Occasionally, some complex conditions may cause relays to perform unintended or incorrect operation, which may further deteriorate the system condition and even jeopardize the stability of the entire system. This paper discusses three categories of solutions for analyzing the relay operation behavior, evaluating and improving the relay performance: 1) relay performance evaluation based on relay testing; 2) field evaluation of relay operation based on advanced fault analysis; 3) automated analysis of relay operation based on expert system. Applications using each solution for the relay performance evaluation are presented to demonstrate the benefits.

KEYWORDS: Protective Relay Testing, Dependability, Security, Expert System, Automated Disturbance analysis

1 INTRODUCTION

Protective relays are designed to meet dependability and security expectations. To meet such performance criteria relays need to be properly applied and set. Occasionally, due to many complex reasons, relays may not perform as intended. This may lead to major problems in the power systems operation, which in the worst case may result in a blackout [1]. Various methods and tools have been developed over the years to avoid such extreme consequences of relay misoperation.

Relay performance evaluation techniques and tools can be used to detect problems with relay settings, applications or design flows. Such techniques may be divided in two broad categories: on-line and off-line. The on-line techniques are focused on relay performance evaluation using recordings from relays or relay monitoring devices such as digital fault recorders [2]. Many innovative techniques, such as wavelet transform based approach [3], synchrophasor based approach [4], and expert system based approach [5] have been introduced either to characterize or improve the relay operation performance. The off-line techniques may use either modeling and simulation approaches or filed-record waveforms to generate relay inputs to be used for relay testing [6]. Many efforts are made on developing various approaches related to the software programs for modeling protective relays and power systems [7], as well as the test equipment for interfacing test data with physical relays [8].

This paper discusses three sets of tools and associated methodologies that were developed over a 15 year time-span. One approach is aimed at acceptance testing of relays using conformance and compliance test cases developed with special attention to the security evaluation of protective relay operation [6]. It is performed using specialized test simulators capable of replaying either simulated or recorded waveforms simultaneously at multiple relays. This type of test may be applied to multi-terminal protective relay applications such as T-feeder configurations for transmission line relaying or tree-terminal protection of power transformers with tertiary windings. The application of this type of tests is illustrated using an IEEE PSRC power system model and a library of test cases generated using this model [9]. The second approach is focused on real-time field evaluation of relay operation during cascading events. It requires tools for monitoring relay operation and comparison with criteria for correct operation. Two cases are considered: relay unintended operation due to line overloading and relay missoperation due to hidden failure. The correct relay operation criteria used for evaluation of unintended operation and missoperation are the real-time implementation of an accurate fault location techniques and fault decision-tree model of relay logic operation respectively. The third approach is

concerned with automated post-mortem analysis of relay operation and fault clearing sequences. It is implemented using an expert system that analyzes records from digital fault recorders or relays to come up with a conclusion whether the relay operation and related fault clearing were as expected. The expert system rules allow cause-effect analysis of various sequential steps in operation of relays, communication channels and circuit breakers. Case studies for the mentioned relay evaluation techniques are presented to demonstrate the advantages.

2 RELAY PERFORMANCE EVALUATION THROUGH TESTING

2.1 Performance Test Methodology

Two different types of tests are defined in terms of the evaluation objectives: conformance test and compliance test. Both types of tests are performed using transient signals [10] which are close to the reality and provide more accurate results than that of traditional methods.

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 set of test cases with a variety of disturbance conditions including fault and non-fault are generated through simulation or collected from the field recordings.

Verifying whether a relay can operate correctly under peculiar circumstances in power system particularly during abnormal operating conditions can be performed with the compliance test. This type of test helps investigate whether a protective relay complies with its expected performance in a given application. The concern of this test is the trip/no trip response and relay operating time performance under specific application scenarios. Selecting vulnerable scenarios which may cause relay unintended operation can be achieved by steady state and dynamic state modeling approach [6].

Two power system models are used to generate various disturbance scenarios for performing the conformance test and compliance test. The reference model created by Power System Relaying Committee (PSRC) is used for the conformance test [9]. Its one-line diagram and simulation model established in ATP are given in Figure 1. The study of selecting vulnerable conditions for the compliance test is achieved by using IEEE 14-bus system [11].

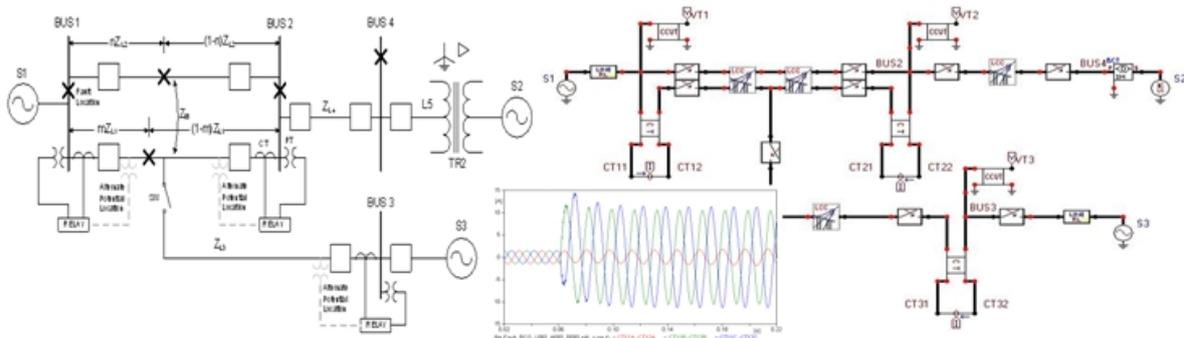


Figure 1: One line diagram and ATP model for IEEE PSRC system

2.2 Relay Test Implementation

The relay test evaluation is implemented on the laboratory setup shown in Figure 2. 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. The block diagram of the batch simulation program developed in MATLAB is given in Figure 2 as well. This program automatically simulates 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 [12], which can be used for multi-purpose study and analysis. A commercial software program called Relay Assistant [13] residing on the PC communicates with digital simulator is capable of sending transient voltage and current data and receiving contact status data. 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.

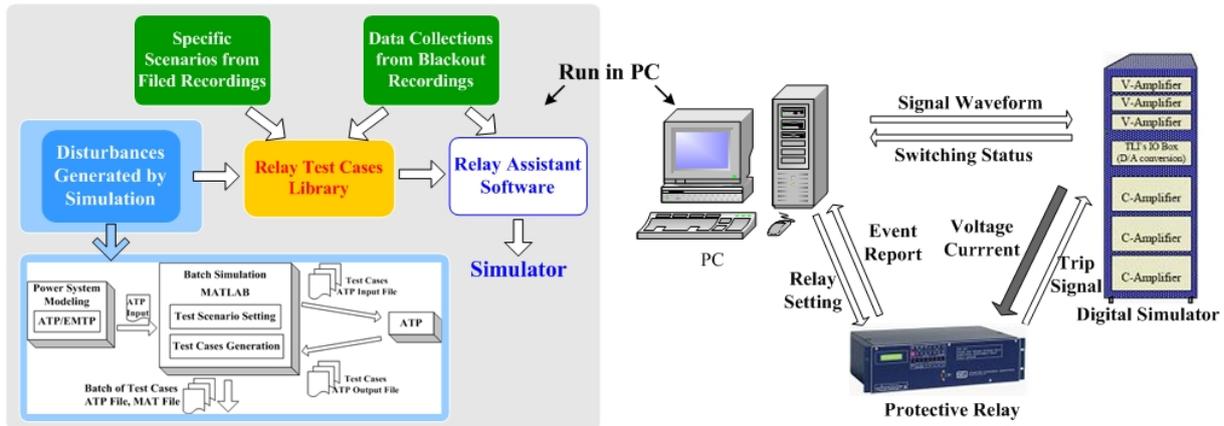


Figure 2: Relay test framework and laboratory setup

2.3 Test Case Library

For each of the relay types considered, a library of power system models and disturbance scenarios is created. As shown in Figure 2, 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.

3 RELAY ON-LINE PERFORMANCE EVALUATION

3.1 Neural Network Based Fault Detection and Classification (NNFDC) Algorithm

Neural network is one of artificial intelligence techniques. The neural network based algorithm classifier is used to detect and classify the disturbances that require protective relay action. Comparing with traditional method, neural network based fault diagnosis algorithms usually uses the time-domain voltage and current signals directly as patterns instead of calculating phasors. The technique compares the input voltage and current signals with well-trained prototypes instead of predetermined settings. Thus accuracy of phasor measurement and relay setting coordination are not an issue in neural network based algorithms as they are not the traditional methods. This provides an advantage of the proposed solution vs. the traditional methods. A self-organized, fuzzy ART neural network based fault detection and classification algorithm has been developed [14], which is shown in Figure 3. Voltage and current signals from the local measurement are formed as patterns by certain data processing method. Thousands of such patterns obtained from power system simulation or substation database of field recordings are used to train the neural network offline and then the pattern prototypes are used to analyze faults on-line by using the Fuzzy K-NN classifier. The use of multiple neural networks can also enhance the capability of dealing with large data set [2].

3.2 Synchronized Sampling Based Fault Location (SSFL) Algorithm

Synchronized sampling based fault location algorithm uses raw samples of voltage and current data synchronously taken from two ends of the transmission line, which provides a very high accuracy in fault detection, classification, and location [15,16]. Compared to the fault location algorithms that use one end or two end phasor data, synchronized sampling based fault location algorithm makes no assumptions about fault condition and system operating state, so it is immune from power swing, overload, and other non-fault situation. This gives an accuracy and robustness advantage of the proposed scheme vs. the traditional one.

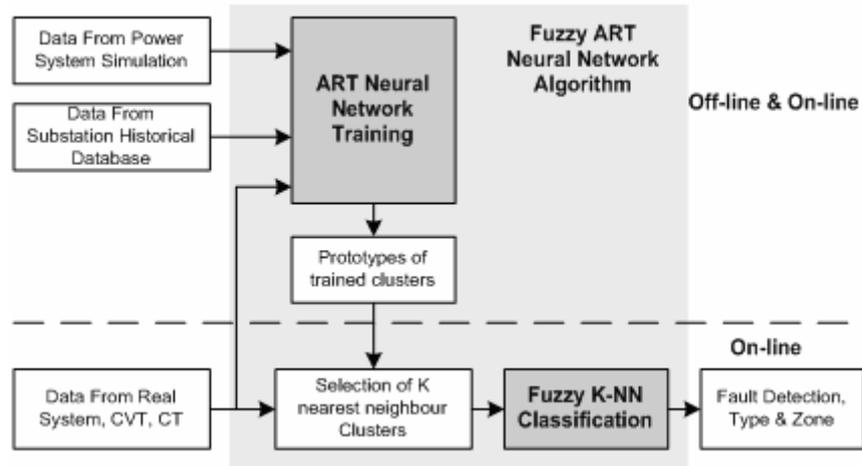


Figure 3: Fuzzy ART neural network algorithm

3.3 Event Tree Analysis

Event tree analysis is a commonly used event/response technique in industry for identifying the consequences following an occurrence of an initial event [17]. The Event Tree Analysis takes the structure of a forward (bottom-up) symbolic logic modeling technique. This technique explores system responses to an initial “challenge” and enables assessment of the probability of an unfavorable or favorable outcome. In our case, the design of event trees is distributed to each single relay system, and it provides an efficient way for real time observation of relay operations and an effective local disturbance diagnostic support.

4 AUTOMATED POST-MORTEM ANALYSIS OF RELAY OPERATION

4.1 Automated Analysis of relay operation

The automated analysis of relay operation is based on the comparison of expected and actual protection operation in terms of statuses and corresponding timing of logic operands. If the expected and actual status and timing of an operand are consistent, the correctness of the status and timing of that operand is validated. If not, certain failure or missoperation is identified and diagnosis will be initiated to trace the reasons by the use of logic of a cause-effect chain.

The conceptual strategy of the post-mortem analysis is illustrated in Figure 4. The expected protection operation is predicted by an expert system module which simulates the operation chain of the protection system. Inputs to this module are disturbance information, relay settings and performance specification of protection system units, which are used to infer the expected statuses and timings of active logic protection operation by forward chaining rules. The results are regarded as hypothesis of protection operation. With both hypothetical and actual operations available, the expert system module performs validation of the correctness of statuses and timings of logic operands based on hypothesis-fact matching. It further performs diagnosis of inconsistency of expected and actual statuses as well as timing of logic operands based on the cause-effect logic. Finally an analysis report is created.

4.2 Expert System based Implementation

In the expert system based application [18], forward chaining reasoning is used to predict expected protection operation, and backward chaining reasoning is employed to validate and diagnose actual protection operation. The detailed application frameworks for the forward chaining reasoning and backward chaining reasoning can be found in [19]. A framework is developed using Visual C++ to facilitate data inputs from relay files and reports, and data outputs to the diagnosis report. CLIP expert system shell is used to perform the major diagnosis analysis [20].

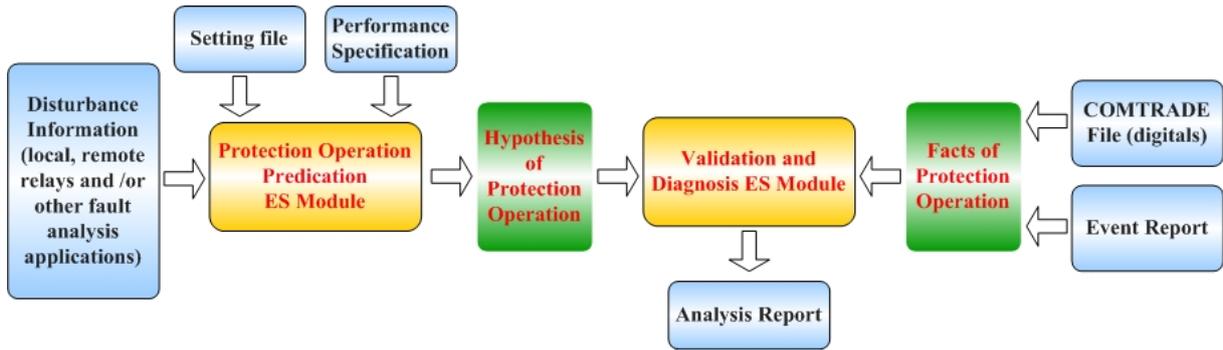


Figure 4: Block diagram for conceptual strategy of post-mortem analysis

5 CASE STUDIES OF RELAY PERFORMANCE EVALUATION

5.1 Relay Testing

Three different distance relays are configured with various protection functions typically used in the field to perform off-line relay test using proposed methodology. An example of results obtained by executing conformance test on one relay is given in Table 1. 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 the tested relay. One can notice very interesting results with respect to differences in operating times for various fault conditions as well as differences between maximal and minimal values of operating time for the same fault condition.

Table 1: 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	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	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	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	90	90	II	30	359.65	361.3	357.2	1.41

Another example of results obtained by applying conformance test is given in Figure 5. It depicts a comparative analysis of trip time vs. fault location for three distance relays. Trip time shown in this figure is obtained statistically after several tests cases are repeated. Relays are set to operate in zone 1 covering 80% of the line. An interesting outcome is that the trip time, for some relays, becomes much longer than expected. These results provided additional information which was not documented in the relay manuals, and definitely may affect proper coordination of the relaying schemes.

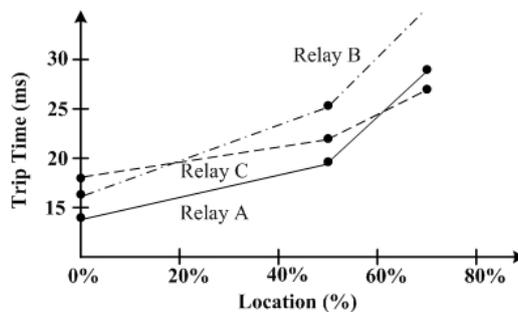


Figure 5: Example of comparative test results

Some relays operated unintended by either over-reaching or under-reaching in some conditions are revealed through the test results of compliance test. It also indicates 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.

5.2 On-line Monitoring of Relay Operation

A case study is given to demonstrate the process of the on-line monitoring and performance analysis of relays by the advanced fault analysis tools [21]. The detailed data requirements and data sources for the implementation are discussed in [22]. The advanced on-line fault analysis tool detects the disturbance by analyzing local measurements. Event tree analysis process is invoked to validate relay operations after the disturbance is detected and classified. Different fault scenarios are generated to test the accuracy of the algorithms. A 500 kV transmission line from Entergy system in United States is chosen as the study model for case generation, which is a tie line connecting the central region with southwest region of Entergy system.

A large number of fault and non-fault cases has been generated to accomplish the training process for NNFDC algorithm, which includes different fault types, fault locations, fault resistance, and fault angles. There are 209 clusters altogether determined with labels of different fault types. Then 5000 cases are tested for the trained neural network. Two classification algorithms are used when performing the test procedures: the nearest neighbor algorithm and fuzzy k-nearest neighbor algorithm. Figure 6 shows the errors for the fault classification for basic nearest neighbor algorithm and fuzzy k-nearest neighbor algorithm. K is set to four.

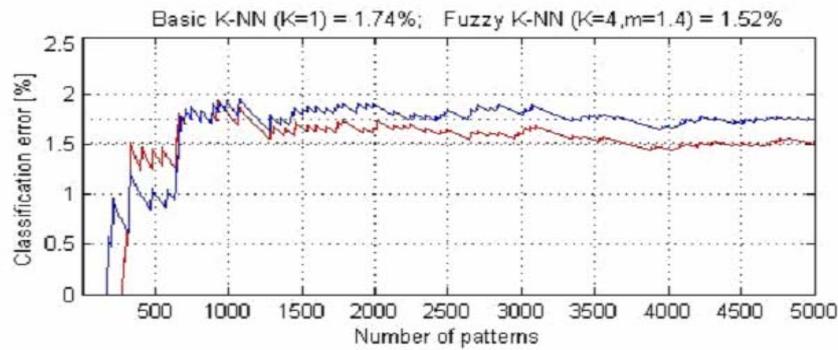


Figure 6: Error results of neural network fault classification tools

SSFL algorithm is also tested based on the same simulated transmission line. 140 fault cases are generated by random setting of parameters. The generated data includes the fault voltages and currents from two sides of the transmission lines, which covers different cases of fault types, fault angles, fault resistance, and fault locations. Table 2 shows 6 cases of the results for SSFL algorithm. For all the test cases, the maximum error for fault classification is 3.6992%; the minimum error is 0.0234%.

Table 2: Results of SSFL algorithm

	Fault Type	Fault Distance (mile)	Fault Resistance (Ω)	Fault Angle (degree)	Fault Location (mile)	Error (%)
1	CAG	85.2	3.1	199.9	85.25	0.0234
2	ABCG	23.1	13.1	38.2	22.51	0.2870
3	AB	38.3	15.1	3.8	37.48	0.3933
4	BCG	19.6	2.5	239.7	21.57	1.0016
5	AG	176.4	9.2	98.5	174.60	0.8917
6	ABCG	68.0	2.3	102.8	66.60	3.6992

5.3 Diagnosis of Relay Operation Using Expert System

A simplified case is used to demonstrate the capability of the relay operation diagnosis. A phase to phase ground fault is generated using the relay testing tools, described in Figure 2

to trigger the relay operation. The disturbance information and diagnosis results are given in Figure 7.

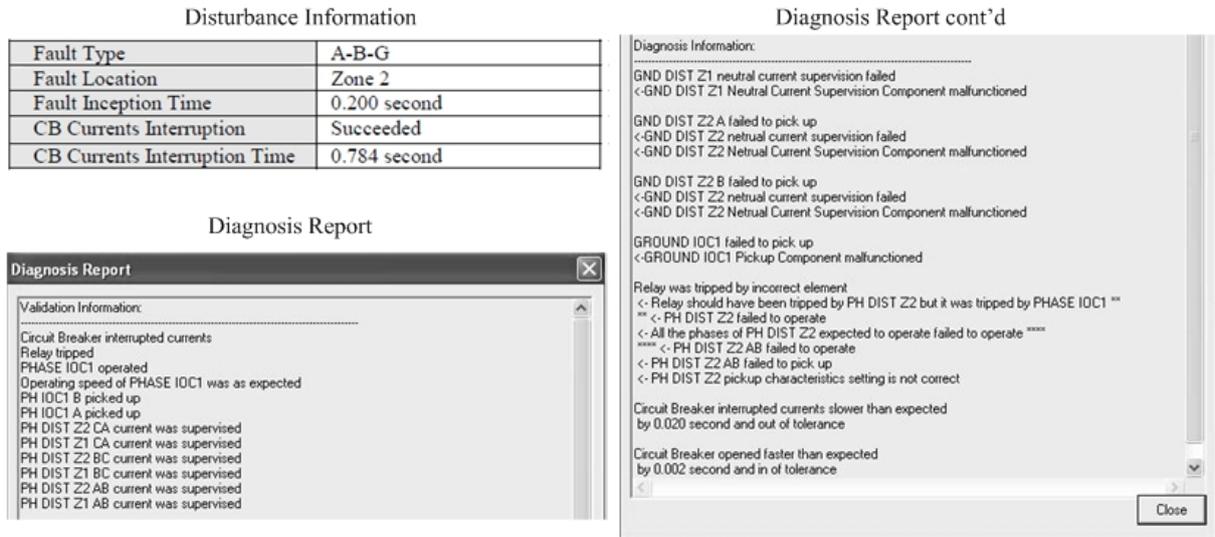


Figure 7: Disturbance information and diagnosis report for relay operation analysis

As shown in the validation information section in Figure 7, PHASE IOC element operated to trip the relay. The circuit breaker opened due to the relay trip and the fault currents were interrupted by the circuit breaker. Several abnormalities were identified and diagnosed as shown in the diagnosis information section. Phase distance zone 2 failed to operate because of the incorrect pickup setting. Ground distance zone 2 should have picked up but failed due to its neutral current supervision failed. Additionally ground IOC element failed as well. Based on these results, it possible indicates that something was wrong with the neutral current channel. There was also timing diagnosis information related to the circuit breaker. It opened a little bit faster than expected but still within the pre-set tolerance. However the delay on interrupting current was out of the pre-set tolerance.

6 CONCLUSION

Three sets of tools and methods for evaluating protective relay performance are presented in this paper. The relay testing based method may help validate the design of the relay logic, characterize the relay operation behavior, verify selection of relay settings and identify vulnerable conditions apt to causing unintended operations. The advanced fault analysis based on-line approach combines neural network based fault detection and classification (NNFDC), synchronized sampling based fault location (SSFL) and event tree analysis. It may help in improving the accuracy of fault analysis under different circumstances. The results of the analysis may be used to make better decisions when performing a corrective action to mitigate incorrect or unintended relay action during cascading events. The expert system based post-mortem analysis of relay operation determines whether the relay operation and related fault clearing actions were as expected through automated analyzing records from digital fault records or relays. It may help to identify incorrect settings and trace component malfunctions.

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