New Solutions for Improved Transmission Line Protective Relay Performance Analysis

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***Abstract*—Transmission line protective relays are assuring normal operation of power system by automatically isolating faulted sections. Different disturbances in power system could affect relay behavior and may result in relay misoperation or unintended operation. This paper explores various aspect of the performance analysis of existing protective relays. Three categories of solutions are discussed: 1) relay performance evaluation based on relay testing; 2) on-line relay monitoring based on advanced fault analysis and relay dynamic performance analysis; 3) intelligent alarm processing based on analysis of the relay logic operands. Case study and benefits are presented for each solution for relay performance analysis to demonstrate the advantages.**

***Index Terms*—protective relaying, performance analysis, relay testing, cascading events, fault analysis, alarm processing**

I. Introduction

THE reliability and security of power system operation may be affected by relay behavior in various ways. Either relay misoperation or unintended operation may be one of the contributing factors for the large area disturbances and cascading blackouts. According to historical records, about 75% percent of the US major power system undesired disturbances are related to protection issues [1, 2]. Better understanding the performance of relays is very important in maintaining the reliability and security of power system.

The existing fault classification and verification in a transmission line protective relay is based on the calculation of the voltage and current phasors. This method is often dependent on the sequence impedances of transmission line. The accuracy may decrease when a disturbance quite different from the expected operating condition happens [3]. Aiming at finding ways to improve the dependability and security of protective relays, different innovative techniques, such as expert system based approach [4], phasor measurement unit based approach [5], and wavelet transform based approach [6] have been used for calcifying and verifying faults. Most of these techniques require very high sampling rate or some other design provision that may not be readily available, so deployment of new techniques seems to be slow. To remedy the situation, new approaches to evaluation of transmission relay operation will assure that the performance of the existing relays is improved.

This paper explores new solutions for performance analysis of transmission line protective relays. The goal is to implement better approaches to testing protective relay behavior, better on-line monitoring of relay operations, and better understanding of the cause-effect analysis of relay operation. The outcome will be an improvement in relay operation, which in turn will allow avoiding misoperations or unintended operations of transmission line protection. Three issues are the focus of this paper: a) relay performance evaluation through improved testing, b) mitigation of cascading events through correction of incorrect or undesirable relay operations, c) the role of relays in the cause-effect analysis for alarm processing solution.

This paper is organized as follows: Section II introduces the importance of protective relaying in power system. Solutions for relay testing, mitigation of cascading events, and alarm processing are discusses in Section III, IV, and V respectively. Conclusions are given at the end.

II. Importance of Transmission Line Relaying

Transmission line relays recognize fault and act locally to isolate faulted power system parts from the rest of the system. This must be done as fast and as accurate as possible to maintain stability. A well designed protective relay is expected to operate correctly for a fault, and not to operate when there is no fault. These two features are called dependability and security respectively [7]. The correct operation of protective relay should clear the fault, as well as reduce and/or eliminate the impact of disturbances on power system. An unintended or incorrect operation may further deteriorate the system condition and jeopardize the stability of the entire system.

Final report on the August 14, 2003 blackout in the north east of the USA indicates that a number of protective relays have not operated as intended [1]. It also indicates that many key transmission lines were incorrectly tripped one after the other by zone 3 distance relay elements, which resulted in an overload rather than faults causing subsequent cascading outages. The reason might have been that the design of the relays was different from what was specified in the manufacture's manuals or the settings were inadequate for the prevailing operating conditions [8]. An improved relay performance assessment is needed to enhance power system security and reliability. Three categories of relay performance assessment approaches are discussed in this paper.

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III. Relay Performance Evaluation Through Testing

A. *Background of Relay Evaluation Needs*

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. Transmission line protective relay operation may be affected by several factors such as the scheme design, operating characteristic selection, setting coordination, application conditions, etc. The mentioned 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 make sure it satisfies the requirements.

B. *New Test Methodology and Setup*

A new test environment for assessing application features of protective relays including test methodology and tools is developed at Texas A&M University. The test tools used for interfacing test data and physical relays are presented below.

1) Test Classification

According to the test objectives two different types of tests are defined: conformance test and compliance test. Both types of tests are performed using transient waveforms [9], which are close to the reality and provide more accurate results than that of traditional based methods [10].

2) Power System Model

A reference model created by IEEE Power Engineering Society's Power System Relaying Committee (PSRC) is used for the conformance test [11]. Fig.1 shows the one-line diagram of the reference model.

The application test is performed by using the IEEE 14-bus system [12], which has 5 synchronous machines, 20 branches, 11 constant impedance loads under 60 Hz power frequency, as shown in Fig.2. Various disturbances related to conformance and compliance tests may be simulated using this model.

3) Test Scenarios

To fulfill these two types of test, extensive set of cases with a variety of disturbance conditions including faults and no-fault conditions which may mangle relay performance are generated through simulation. A batch simulation program used for automatically generating disturbance scenarios is developed in MATLAB [12]. The ATP is used to generate transients [13]. The output format of waveforms can be PL4, MAT and COMTRADE, which can be used for multi- purpose study and analysis [14].

4) Test Setup

The major components of test setup include a PC used to run related software, a digital simulator used to generate "real" voltage and current signals and the physical relay under test as shown in Fig.3. Relay Assistant software is used to perform automated relay testing [15].

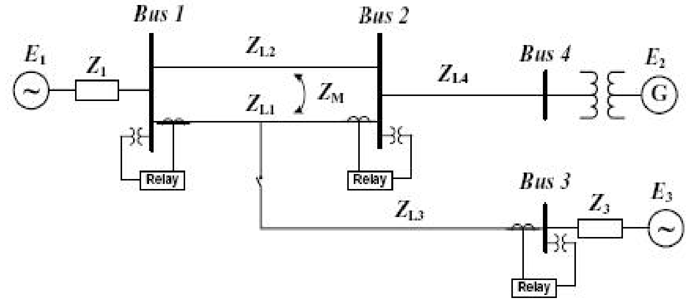

Fig. 1. One line diagram for IEEE PSRC system

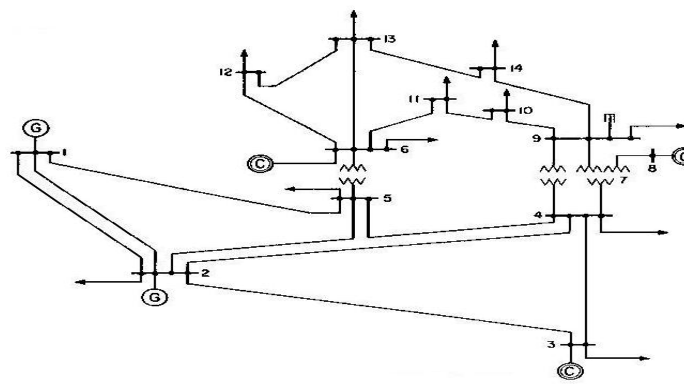

Fig. 2. One line diagram for IEEE 14-bus system

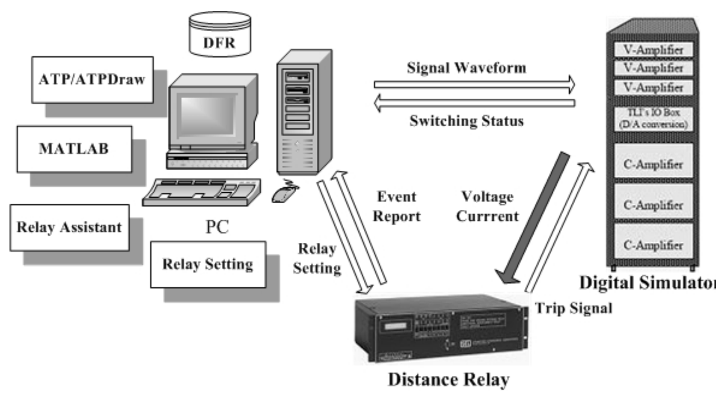

Fig. 3. Test setup for physical relay test

C. *Case Study and Benefits*

A sample of a test case of applying conformance test on distance relay using proposed methodology is discussed using the test results given in Table I.

TABLE I
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

In this case, different test scenarios 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. 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.

The test environment presented in this paper allows: accurate modeling of the power system used to generate test cases, easy simulation and replay of disturbances, interface between relays and power system models, and automatic execution of batch tests and collection of relay responses. This enables an effective approach to evaluating protective relay performance under changing power system conditions.

IV. Mitigation of Cascading Events Through On-line Monitoring

A. Background of the Needs for Analysis of Cascading Events

Cascading blackout is an undesirable condition that may cause great economic loss in power system operation and may have devastating impact on people's life. For example, Northeastern Blackout in 2003 led to the load loss of 61.8GW, which influenced more than 50 million people [1]. Many factors such as lack of understanding of unfolding events, insufficient operational awareness, inadequate tree trimming, unexpected relaying problems, bad weather conditions, human errors, etc may cause cascading events [1, 2]. It was determined that relay misoperation or unintended operation may contribute the most to the cascading outages. On-line monitoring of relay performance is extremely important when studying the processes and causes of cascading events.

Having such monitoring means is critical for assuring a secure and reliable operation of power systems.

B. On-line Relay Monitoring and Evaluation

Conventional solution for transmission line protection is based on calculation of relay setting using predetermined worst case fault scenario assumptions. Once set, the relays will make their decisions based on local measurements without knowing or considering what is actually happening with the entire system condition. In certain situations, these decisions may not be appropriate from the view point of the whole system reliability consideration, which could result in relay misoperations or unintended operations leading to a system blackout.

A new on-line monitoring and evaluation scheme for the relay operation during cascading events is developed at Texas A&M University recently. It coordinates the system-wide and local monitoring and control tools, especially system security and local protection. [3, 16]

For system-wide analysis, the vulnerable transmission lines due to stressed operation conditions are identified by a steady state approach utilizing the power flow method and topology processing method [17]. The security analysis tool is based on Vulnerability Index and Margin Index that help find the critical transmission lines, which are more vulnerable to the disturbances [18]. This information is sent to the local analysis tool that performs on-line monitoring and performance analysis of related relays. The tool utilizes the neural network based fault detection and classification (NNFDC) and synchronized sampling based fault location (SSFL) algorithms as shown Fig. 4 [19,20]. NNFDC should accomplish the training process by using a variety of scenarios from different faults parameters.

The advanced on-line fault analysis tool will detect the disturbance by analyzing local measurements. The input can be waveforms obtained by relay or synchronized digital fault recorders (DFRs). Once the disturbance is detected and classified, event tree analysis process will be invoked to validate relay operations. The combination of the two algorithms performs a more accurate fault analysis than conventional relays do. This provides a reference for monitoring and verification of the distance relay operations.

For those vulnerable transmission lines, the possible relay operations can be verified by performing dynamic analysis of relay behavior. Dynamic bus voltage phasors are calculated from the time-domain transient stability analysis. They are used to calculate the apparent impedance seen by distance relay and obtain the dynamic impedance trajectory [21].

C. Case Study and Benefits

A case study of relay dynamic performance analysis is based on the standard IEEE 39-bus New England System, as shown in Fig.5.

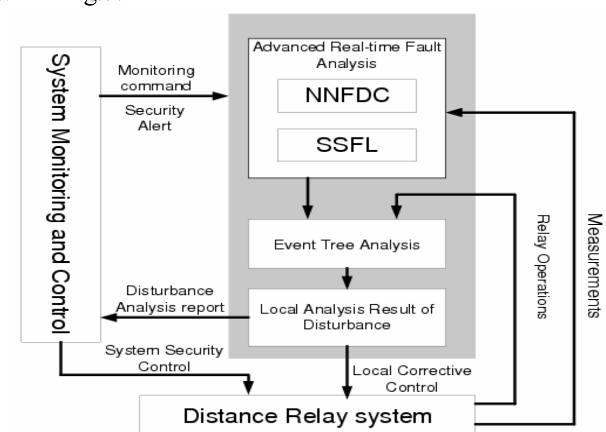

Fig. 4. Block Diagram of Local Monitoring and Control

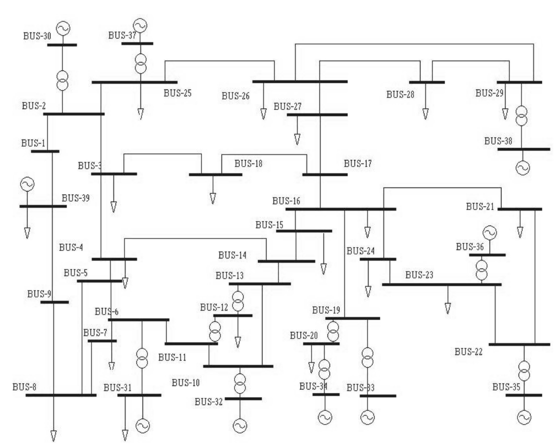

Fig. 5. IEEE 39-bus New England System

When disturbances happen, the relay dynamic performance tool is utilized to verify relay operations. The analysis results are used as additional reference when collecting relay operation results by local monitoring tools located at the substation where the relays are placed. A fault scenario is created to demonstrate that relay may misoperate under certain conditions.

The fault scenario is generated as 3-phase fault occurs at 50% of L27 (B22-21) at t=0s, and gets cleared by tripping L27 at t=0.12s; another 3-phase fault occurs at 5% of L34 (B29-28), close to bus 29 at t t=1.0s, and gets cleared by tripping L34 (B29-28) at t=1.016s.

The trajectory of impedance seen by the relay at bus 26 (B26) of L33 (B29-26), which is shown in Fig. 6, indicates why the relay will misoperate. If the relay setting time is shorter than the time that the fault impedance stays in the zone 2 or zone 3 circles, the distance relay will trip L 33 according to its algorithm.

The disturbance data obtained from DFRs and relays will be used by relay dynamic performance analysis tool. If fault analysis tool based on NNFDC and SSFL does not detect the fault in the primary or backup zone, and relay dynamic performance analysis shows the fault impedance will stay in the trip circle of relays, relay misoperation may happen and relay monitoring is activated. Possible relay operation correction may be initiated. This action will be aimed at mitigating the disturbance and keeping the system secure.

V. Improved Alarm Processing Through Cause-effect Analysis of Relay Operations

A. Background of Alarm Processor Needs

With the growth of power system complexity, operators are often overloaded with alarm messages generated by the events in the system. A major power system disturbance could trigger hundreds and sometimes thousands of individual alarms and events [22]. Obviously, this is beyond the capacity of any operators to handle. Thus, operators may not able to respond to the unfolding events in a timely manner, and even worse, the event interpretation by the operators may be either wrong or inconclusive. The task of an intelligent alarm processor is to analyze thousands of alarm messages and extract the information that concisely explains the network events.

B. Improved cause-effect analysis using relay data

A lot of research has been done on the Fuzzy Reasoning Petri-nets (FRPN) [23-25]. FRPN takes advantages of Expert System and Fuzzy Logic, as well as parallel information processing to solve the problem of fault section estimation. Reference [26] gives an optimal design of a structure of FRPN diagnosis model. It has been proven that the logic operand data of digital protective relays can be used as additional inputs to enhance the alarm interpretation [27].

A 14-bus power system as shown in Fig. 7 is used for the study of fault section estimation problem. The system consists of 34 sections, including 14 buses and 20 transmission lines. The buses are denoted as Bnn. The transmission lines are denoted as Lnnmm.

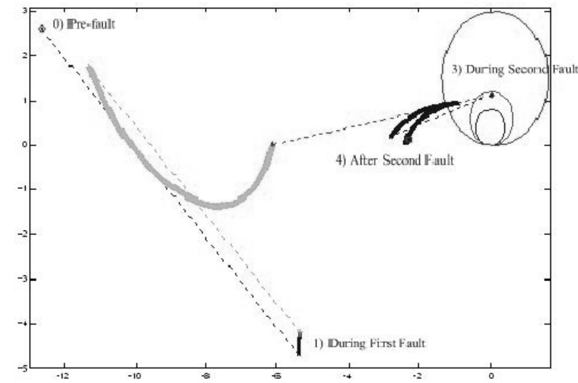

Fig. 6. Apparent impedance seen by distance relay at B26 of L33

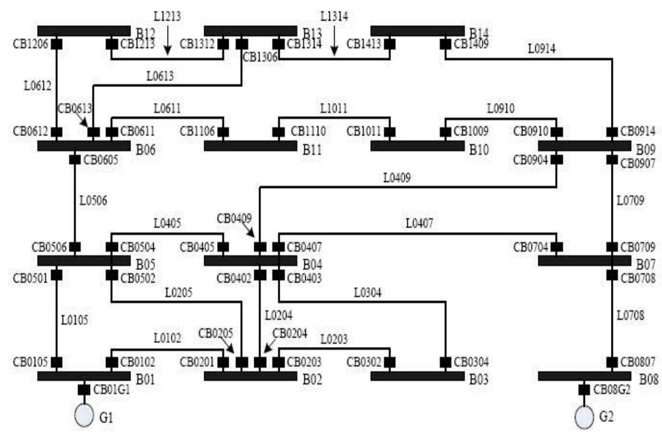

Fig.7. A 14-bus power system model

We use backward reasoning concept to structure the FRPN diagnosis models and generalize the design for transmission lines and buses [28]. The 'AND-OR' structure concisely represents all the possible combinations of main, primary backup and secondary backup protection operations for inferring a fault.

Based on the proposed structure, all the FRPN diagnosis models are developed. As an example, Fig. 8 shows the FRPN models for the transmission line L1314.

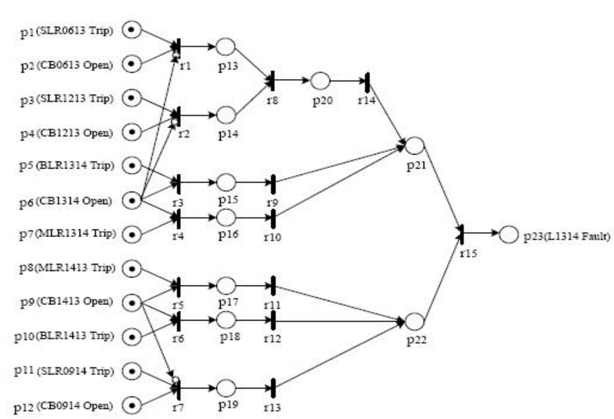

Fig.8. A FRPN model for L1314 fault based on SCADA data

In a digital protective relay, the pickup and operation information of protection elements is usually in the form of logic operands [29]. The pickup and operation logic operands are more reliable than SCADA data because they are more redundant and have less uncertainty than relay trip signals and circuit breaker status signals. They can be utilized to improve the accuracy of fault section estimation based on SCADA data, as shown in Fig.9.

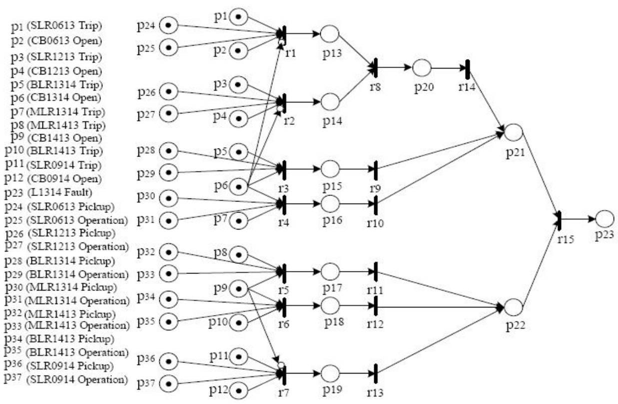

Fig.9. A FRPN model for L1314 fault based on SCADA and digital protective relay data

When a fault occurs on the transmission line L1314, its associated protection system operated to respond to the fault. In addition to the observed SCADA data, the following relay signals are also observed: SLR0613 Pickup, SLR0613 Operation, SLR1213 Pickup, SLR1213 Operation, BLR1314 Pickup, BLR1314 Operation, MLR1314 Pickup, MLR1314 Operation, MLR1413 Pickup, MLR1413 Operation, BLR1413 Pickup, and SLR0914 Pickup. Since the relay data are more reliable than the SCADA data, they are given a larger truth value 0.98

If MLR1413 Trip is missing in the SCADA data due to data transmission error while MLR1413 Pickup and MLR1413 Operation are observed, the conclusion will be that a fault occurs on the transmission line L1314 with a truth degree value 0.827.

C. Case Study and Discussion

Based on the approach introduced in [27], a power system/protection system interactive simulation environment for the case study has been developed. The evaluation environment enables one to set up fault scenarios, insert user-defined errors, and generate SCADA data and relay data.

A permanent fault occurred on the bus B04 at 0.05 second. A second permanent fault occurred on the bus B09 at 0.09 second. All the protection devices operated correctly. No false data occur. The observed SCADA data are listed in Table II. The observed relay data are listed in Table III.

Based on the SCADA data in Table II, the candidates for the fault section are estimated and results are listed in Table IV. Based on both the SCADA data in Table II and relay data in Table IV, the candidates for the fault section are estimated and the results are listed in Table V.

As shown in Table IV and Table V, besides the bus B04 and the bus B09, on which faults actually occur, the transmission line L0409, which has no fault, is included in the candidate set. The transmission line L0409 has a far smaller truth degree value than the other two candidates, which indicates small possibility of fault occurrence. The truth degree values of the candidates based on both the relay data and SCADA data are higher than those based on only the SCADA data.

TABLE II
SCADA DATA FOR CASE STUDY

Sequence No.	Time Stamp (Sec)	Observed Signal
1	0.1000	BR04
2	0.2000	CB0402
3	0.2000	CB0403
4	0.2000	CB0405
5	0.2000	CB0407
6	0.2000	CB0409
7	0.2000	BR09
8	0.2000	CB0904
9	0.2000	CB0907
10	0.2000	CB0910
11	0.2000	CB0914
Sequence No.	Time Stamp (Sec)	Observed Signal

TABLE III
RELAY DATA FOR CASE STUDY

Sequence No.	Time Stamp (Sec)	Observed Signal
1	0.0537	BR04
2	0.0625	SLR0304
3	0.0651	SLR0904
4	0.0667	SLR0204
5	0.0667	SLR0504
6	0.0677	SLR0704
7	0.0703	BLR0704
8	0.0703	BLR0904
9	0.0766	BLR0204
10	0.0766	BLR0504
11	0.0771	BLR0304
12	0.0938	BR09

TABLE IV
CANDIDATES FOR ESTIMATED FAULT SECTIONS BASED ON SCADA DATA

Candidate No.	Fault Section	Truth Degree Value
1	B04	0.855
2	B09	0.855
3	L0409	0.513

TABLE V
CANDIDATES FOR ESTIMATED FAULT SECTIONS BASED ON SCADA DATA AND RELAY DATA

Candidate No.	Fault Section	Truth Degree Value
1	B04	0.882
2	B09	0.882
3	L0409	0.618

VI. CONCLUSION

This paper explores the importance of protective relay in power system and explains the need for and use of enhanced relay performance analysis tools and methodologies. Three categories of applications for relay performance analysis are presented in this paper.

Relay performance evaluation based on relay testing helps 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 better understanding of unintended or incorrect relay behavior.

Relay on-line monitoring based on advanced fault analysis, which combines neural network based fault detection and classification (NNFDC), synchronized sampling based fault location (SSFL), fault tree analysis and relay dynamic performance analysis improves 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 undesirable relay action during cascading events.

Intelligent alarm processing,, which integrates the logic operand data of digital protective relays with traditional data from remote terminal units (RTU) of supervisory control and data acquisition systems (SCADA), enhances accuracy when analyzing the alarm messages and recognizing the nature of disturbances.

VII. Acknowledgements

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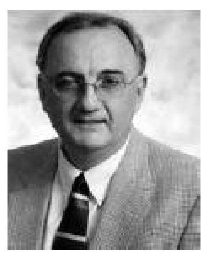
IX. Biographies



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