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End-to-End Testing of High Speed Pilot Relaying - Tutorial and Lessons Learned

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***Abstract*-- A high percentage of the number of misoperations observed on EHV pilot relay schemes can be attributed to a single failure of a component in that scheme. GPS synchronized relay testing of the entire scheme significantly improved the reliability and performance of these transmission systems by allowing the protective relay and power line carrier systems to be tested as a whole. GPS synchronized secondary injection testing of communicated assisted relay schemes such as DCB and POTT is presented. During commissioning or routine testing, this technique can verify the performance of the transmitter / receiver, protective relay, line tuner, coax cable, and auxiliary relays. This testing will also identify signal propagation delays and attenuation. A tutorial is presented to utilize this technique on two, three, and even four terminal lines. A variety of simulated faults computed from a short circuit program are replayed through a relay test set while the scheme's performance is observed through event reports recorded in the microprocessor based protective relay. This valuable tool will certify the scheme for all the fault types at a variety of internal and external fault locations. Lessons learned, problems identified, and misoperations prevented are presented along with techniques to keep the testing running smoothly and record the results.**

***Index Terms*—Pilot relaying, End-to-End testing, Power Line Carrier, GPS Satellite Synchronized, Directional Comparison Blocking, Permissive Over Reaching Transfer Trip.**

I. INTRODUCTION

FIRSTENERGY Corp. is a diversified energy company headquartered in Akron, Ohio. Its subsidiaries and affiliates are involved in the generation, transmission and distribution of electricity, energy management and other energy-related services. Its seven electric utility operating companies, as shown in Fig. 1, comprise the nation's fifth largest investor-owned electric system, serving 4.5 million customers within 36,100 square miles of Ohio, Pennsylvania and New Jersey; and its generation subsidiaries own or operate more than 14,000 megawatts of capacity. The two control areas in FirstEnergy's operating companies' service areas are part of two of the nation's major independent transmission system operators – the Midwest Independent Transmission System Operator (MISO) and PJM Interconnection LLC (PJM). FirstEnergy companies own approximately 12,000 miles of high-voltage transmission lines (69 kV and above), with 94 interconnections and ties to 13 other electric utility systems.

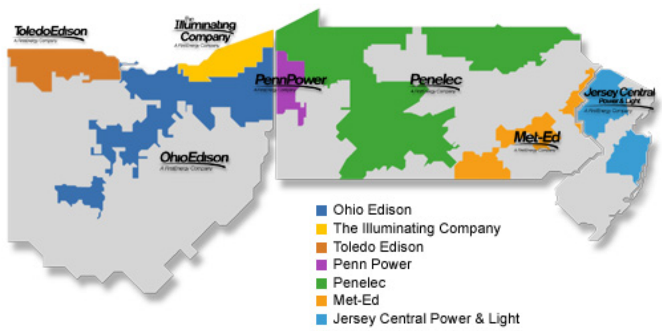

Fig. 1. FirstEnergy Operating Territory

Substation maintenance relay engineers, part of the Energy Delivery Substation Maintenance Department, are taking advantage of the satellite-based technology to successfully improve the reliability and performance of the transmission system. The relay maintenance group consists of 8 engineers and 84 technicians who are responsible for installing, maintaining, and testing all protective devices in the utility's substations and power plants throughout the company's transmission and distribution system.

FirstEnergy moved to End-to-End testing of EHV pilot relay schemes in 2002[1]. The testing is performed when commissioning new microprocessor relay schemes such as Directional Comparison Blocking, DCB, or Permissive Over Reaching Transfer Trip, POTT, schemes. The testing is also performed to diagnose root cause of relay misoperations and over trippings on microprocessor and older electromechanical relay schemes in service at transmission stations across FirstEnergy. The company also utilizes steady-state testing to verify individual elements of individual relays to prove correctness of operation as traditionally performed by other electric utility companies [3]. The inadequacy of steady-state testing is that, while it tests the components of the system, the protective relaying system is never tested as a whole. Therefore, it is not possible to predict with confidence how the entire system will perform under power system conditions [3].

II. Method

Prior to the advent of satellite synchronized relay testing, the protection system was never tested as a whole, so no conclusion could be drawn as to how the system would actually operate under system conditions. Manual testing of individual relay elements of individual relays would lead to the assumption that if the individual components passed their tests that the system would operate correctly as a whole during fault conditions [3].

The introduction of the new digital microprocessor based multi-function relay adds additional hurdles for the relay scheme to properly operate. With the traditional electromechanical schemes, the EM relays and power line carrier transmitter/receiver were matched to a particular manufacturer at each end to the transmission line. Now with change outs of older EM relays, it is possible to mix new microprocessor relays with older existing carrier sets or even with relays from other manufacturers at opposite ends of the transmission line. It is now possible to measure relay targets and control circuits of EM relays with Target Information Sensors (TIS) [4] to validate test results in these legacy systems. The plethora of relay setting possibilities and carrier set start and stop logic schemes can lead to undesirable performance of the scheme and jeopardize the reliability of the transmission system.

FirstEnergy performs End-to-End testing to verify the performance of the entire protection scheme including relay and communication equipment. Individual components include the power line carrier transmitter, receiver, line trap, line tuner, coax cable, auxiliary relays, and line distance relays as shown in Fig. 2.

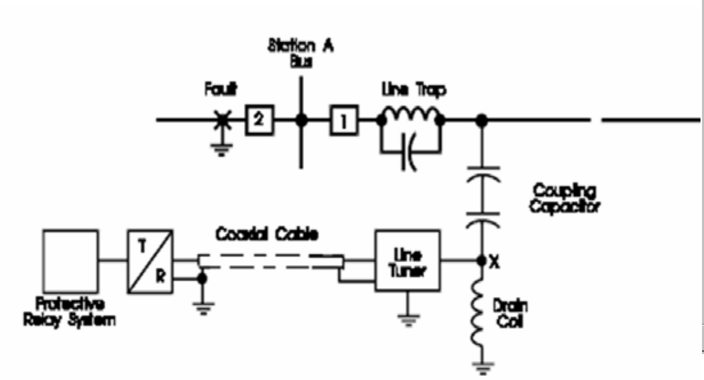

Fig. 2. Pilot relay components

Propagation delays and signal attenuation of the power line carrier signal is also measured and evaluated during the testing.

FirstEnergy performs the End-to-End testing using GPS satellite synchronized secondary injection using a Doble F6150 relay test set along with the optional GPS satellite antenna at each end of a two-terminal line as shown in Fig. 3.

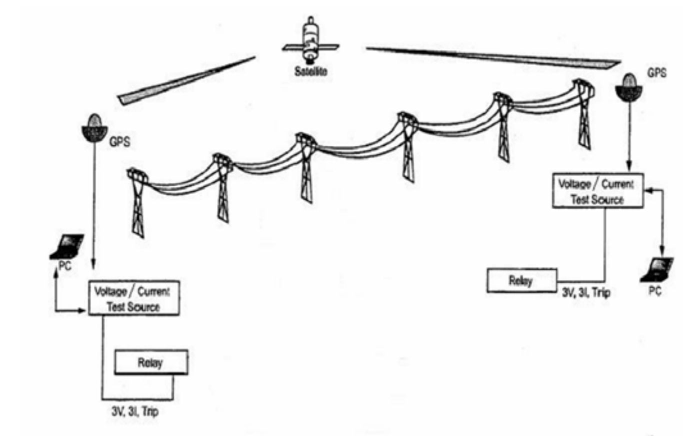

Fig. 3. Testing setup for a two-terminal line with a DCB protection scheme and power line carrier.

Test files for the relay test set are created in Doble ProTest software using the state simulation macro, SSMIL. Fault data is prepared for a variety of internal and external faults using a short circuit program such as CAPE. The fault duration is set to 5 cycles to coincide with proper operation of the high speed relay scheme. The fault duration can be set much longer, say 30 cycles, to test backup relay elements in the scheme if desired. A typical test macro is shown in Fig 4.

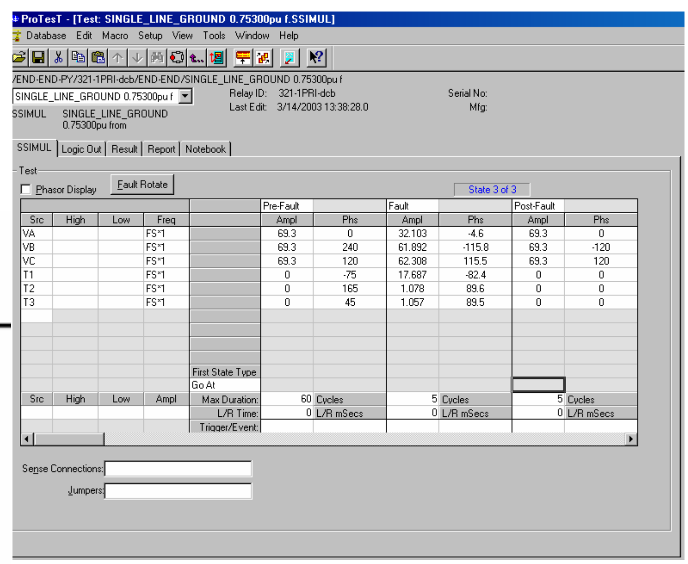

Fig. 4. Typical State Simulation Test Macro.

To properly test the relay scheme for the various internal and external faults possible on the power system, test macros should be generated for line-to-ground, line-to-line, and three-phase faults in different relay zones of the relays such as forward zones one and two, and reverse zone three as seen from each end of the transmission line. Bus faults at each of the line may also be simulated since these may challenge the capabilities of the protective relay. It is common for

FirstEnergy to simulate over 20 faults for a two-terminal line. Often line protection on a 345kV line incorporates a DCB as the primary line protection and a POTT scheme as the backup line protection. These schemes may utilize power line carrier on the primary scheme and microwave on the backup scheme. Sometimes the primary and backup protection will use SEL mirrored bits over fiber optic as the communication medium. These schemes can be individually tested with the same test macros for each scheme. Typical fault locations are shown in Fig. 5 as shown below.

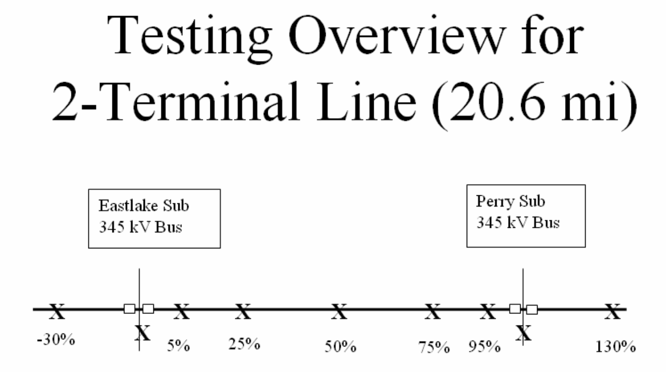

Fig. 5. Typical Fault Locations

FirstEnergy has also tested three and four terminal lines with a combination of microprocessor and EM relaying involving interconnections with neighboring utilities. Some interconnections involve microprocessor relays of different manufacturers. Some End-to-End testing with neighboring utilities involves test with different relay test set manufacturers. A test setup for a three-terminal line and typical fault locations are shown in Fig. 6 and Fig. 7 respectively. End-to-End testing was successfully performed on a four-terminal line as shown in Fig. 8 using four Doble F6150 satellite synchronized relay test sets simultaneously. The transformer high side lead protection was utilized to send carrier block trip for ground inrush during energization of the tapped transformer. The 67N2 ground element was set to start carrier for 20 cycles if the transformer MOAB and circuit switcher had just closed.

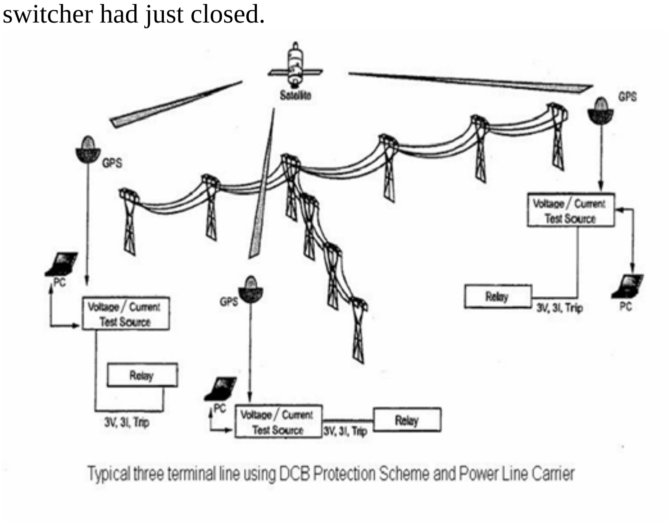

Fig. 6. Test Setup for a Three-Terminal Line

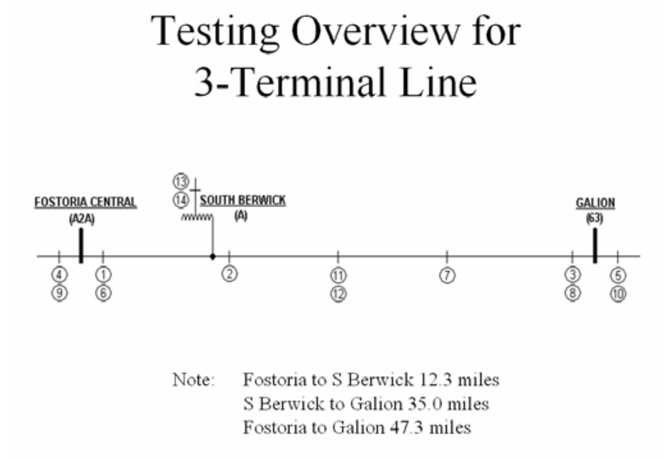

Fig. 7. Typical Fault Locations for a Three-Terminal Line

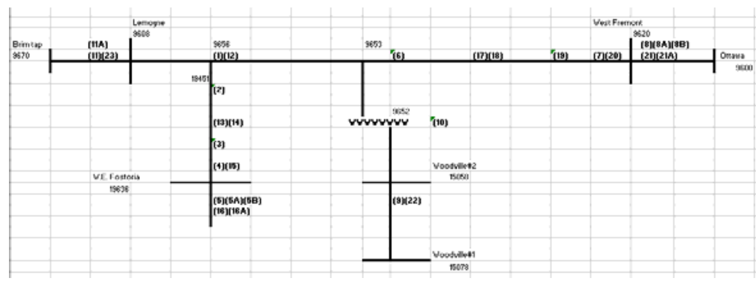

Fig 8. Typical Fault Locations for a Four-Terminal Line

III. Test Preparation

1) *Plan for expected operation* – Study the relay's tripping scheme, logic, and input & output equations to understand how the relay will operate for internal zone 1 and zone 2 faults and external zone 3 faults.

2) *Plan for expected results* – Understand what relay targets and event reports will be expected for the various internal and external faults that will be simulated during the End-to-End testing.

3) *Summarize results* - Have a method or format for recording the results of the End-to-End testing and the relay event oscillography corresponding to the various faults.

4) *Study Oscillography*- Review the relays event reports to ensure that the DCB or POTT scheme is operating as expected and that the appropriate block trip or permissive trip signals are being sent and received as expected. Fig. 9 and Fig. 10 show expected results of the DCB scheme for faults at 130% and 95% of the line length respectively. Fig. 11 and Fig. 12 show expected results of the POTT scheme for faults at 95% and -30% of the line length respectively.

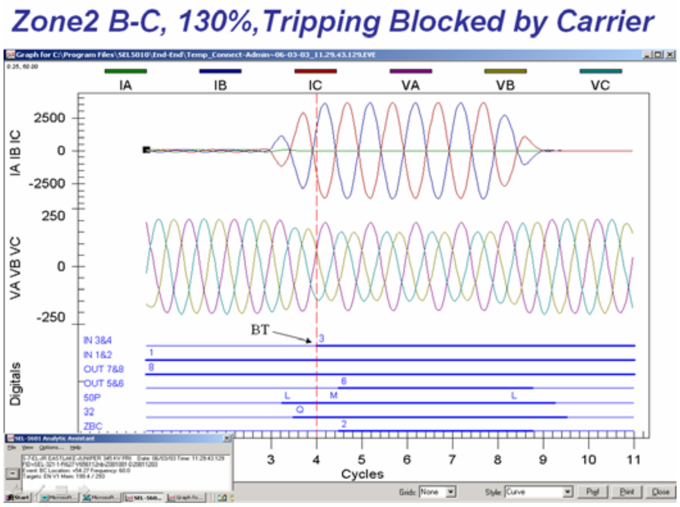

Fig. 9. Relay event report showing successful operation of the DCB scheme for an external line fault.

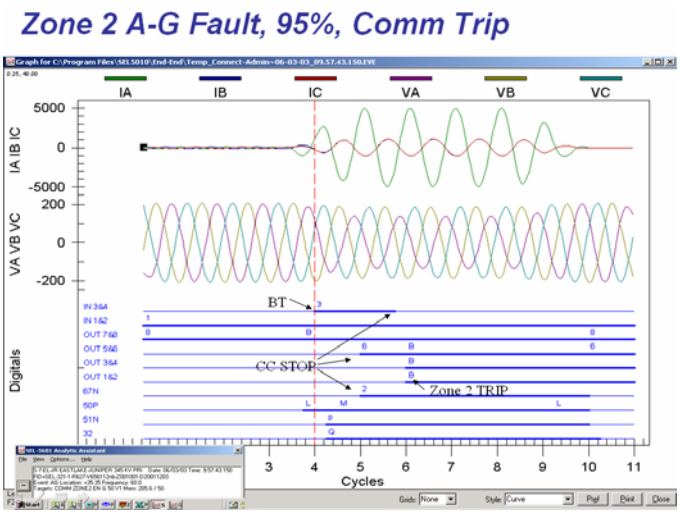

Fig. 10. Relay event report showing successful operation of the DCB scheme for an internal line fault.

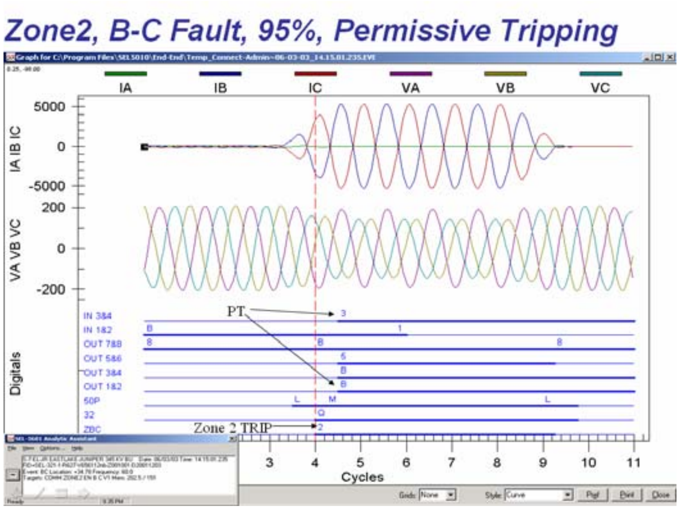

Fig. 11. Relay event report showing successful operation of the POTT scheme for an internal line fault.

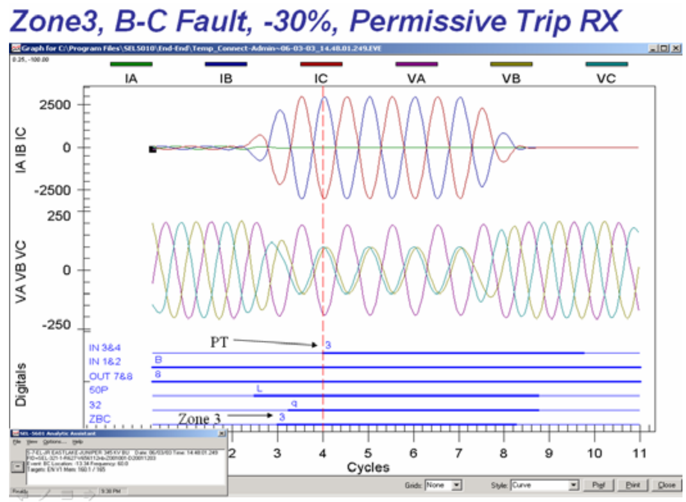

Fig. 12. Relay event report showing successful operation of the POTT scheme for an external line fault.

IV. Dynamic Relay Testing

Modern relay systems are multi-function digital devices that are designed to provide complete protection for a power system component. Some of the newer designs have over 2,000 setting possibilities and require extensive configuration and setting procedures. The traditional method of testing individual steady-state calibrations, one at a time, is no longer a viable method because of the excessive time it would require to reconfigure for each individual element tested. In addition, traditional test methods were designed on the assumption that users did not have test equipment for testing relays under power system conditions. So, traditional test procedures were developed using basic test equipment components such as variacs, phase shifters, and load boxes [4].

End-to-End relay testing utilizes dynamic relay testing techniques simultaneously at each terminal of the transmission line. Dynamic relay testing means testing under true simulated power system conditions. Depending on the level of testing required, test values can be easily calculated by a relay engineer with PC-based short circuit program. For dynamic-state testing, a short circuit program would be used to calculate the fundamental component of voltage and current values for pre-fault and fault conditions. Dynamic-state testing simulations provide a faster and more meaningful way to test relays and relay systems. These techniques provide the user with a far better understanding of how the relay system performs and can aid both relay application and test engineers in evaluating relay operations [4].

Dynamic-state test is defined as simultaneously applying the fundamental frequency component of voltage & current that represents power system states of pre-fault, fault and post fault. Utilizing this technique results in faster relay testing because, in most cases, relay elements do not need to be disabled in order to test a relay function[4].

V. Results

A. Problems Found / Misoperations Prevented

1. Relay Setting Errors – The 50H overcurrent supervisory element used for stub protection on a line connected to a ring bus was set too low. This element, used in the unconditional trip logic, reached into Zone 2 causing overtripping for external faults.
2. Auxiliary Carrier Relay caused unacceptable delays in receiving the Block Trip and caused overtripping of the line - While testing an installation of new line relays, testing showed that the line relaying was overtripping for faults external to the line. The carrier block signal was not being received at the remote terminal before the zone 2 delay timed out (1cycle). It was found that the A&E design firm had removed the BCA relay with high speed contacts and used a contact from a slower MG-6 auxiliary relay connected between the carrier set's output and the relay's input. The auxiliary relay was adding additional 2 cycle propagation delay which caused the scheme to fail. The scheme was redesigned without the auxiliary relay.
3. DCB not enabled on other end of Tie-Line - While testing a DCB scheme on an interconnection tie-line to another utility, it was found that the line relaying misoperated and tripped for all external faults. The investigation found the block signal was not being sent or received at the remote terminal since the DCB scheme had not been enabled in the relays logic.
4. Relay Settings were never modified on other end of Tie-Line - While testing a DCB scheme on an interconnection tie-line to another utility, it was found that the phase distance elements at the remote relay had not been programmed with the reaches for the transmission line. This caused the relay scheme to misoperate for a many of the simulated faults.
5. Carrier Checkback interfering with Start/Stop - While testing a DCB scheme on a two-terminal line, it was found that the scheme was overtripping for external faults. The investigation revealed that the block trip signal was dropping out prematurely. It was found that the carrier set's checkback feature was improperly programmed.
6. Fast Electronic Outputs not operating Old Carrier Sets - While testing a DCB scheme involving new microprocessor line relaying with existing older carrier sets, it was found that the carrier block signal was not being started for external faults. The investigation found that the fast electronic outputs would not shut off the DC voltage to the carrier start circuit when operated. The carrier start circuit was rewired to standard output contacts on the same relay.

B. Lessons Learned

1. You must pay attention to details and plan the end-to-end testing in advance
2. Develop fault diagrams and a table or list of expected relay operations for each fault
3. Develop a method to record results in advance and record the time each fault was applied.
4. Pay attention to a test macro's "Go-At" time vs. the relay's time stamp.
5. Take advantage of the relays event capture to verify proper operation of the scheme.
6. Establish a phone bridge/conference line for testing lines of three or more terminals.
7. The fault duration in test macros affects which relay elements operate, i.e. backup protection may operate for a fault past the remote terminal.

VI. Conclusion

1. End-to-End Testing is a valuable tool to verify that the scheme is working properly and that it works as it was planned.
2. End-to-End Testing verifies that the communication signals are sent and received properly and that there are no problems with communication equipment.
3. End-to-End Testing verifies that the protection operates correctly for faults at all parts of the line.
4. End-to-End Testing verifies that the entire scheme is functionally tested instead of testing individual components.
5. Additional Amplifiers are often needed to perform testing on the high burden electro-mechanical relay schemes.
6. End-to-End testing does not catch common wiring errors found during In-Service Load Checks, open connections on CT neutrals, or other wiring errors such as an incorrectly wired scheme cut-off switch.

V. Acknowledgment

The authors gratefully acknowledge the contributions of James M. Kinney, FirstEnergy Corp., for his work on the original version of this document.

VI. References

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VII. Biographies

Dr. Allen G. Morinec, P.E., has worked at FirstEnergy Corporation since 1986 and his fields of interest include Power Quality, Industrial and Commercial Power Systems, National Electrical Code, Power System Protection, and Substation Maintenance. He assisted in the development of 6 IEEE standards and has authored 9 technical papers. Dr. Morinec is a Senior Member of the IEEE and was awarded the "IEEE Third Millennium Medal for Outstanding Support and Achievement". He was awarded the Willard R. Holland Entrepreneurial Excellence Award for improving FirstEnergy's competitiveness and reliability by implementing GPS synchronized end-to-end relay testing of high speed transmission protection schemes, 2006. Dr. Morinec received his BSEE, MSEE, and DRE degrees from Cleveland State University in 1986, 1989, and 2005.

A.T. Giuliante is president and founder of ATG Consulting (previously ATG Exodus). Prior to forming his company in 1995, Tony was Executive Vice President of GEC ALSTHOM T&D Inc. - Protection and Control Division, which he started in 1983. From 1967 to 1983, he was employed by General Electric and ASEA. In 1994, Tony was elected a Fellow of IEEE for "contributions to protective relaying education and their analysis in operational environments." He has authored over 50 technical papers and is a frequent lecturer on all aspects of protective relaying, including electromechanical, solid state and digital based equipment. Tony is a past Chairman of the IEEE Power System Relaying Committee 1993-1994, and past Chairman of the Relay Practices Subcommittee. He has degrees of BSEE and MSEE from Drexel University 1967 and 1969.

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