A Troubleshooting Methodology for Issues Discovered During End-to-End Testing

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Abstract—Transmission line protection is a critical part of maintaining power system stability. A number of system components are taken into consideration when creating protective settings: capacitive/reactive series elements, accurate power system modeling, varying standards between interfacing utilities, etc. Due to the varied nature of network topology, it is crucial that line relay settings are tested in a manner that will reflect actual use. The best way to test the protective intent of these settings is through fault simulation, or "end-to-end" testing.

There are a number of issues that can be discovered by performing end-to-end commissioning of protective line settings. This paper will provide real examples of problems found during line relay commissioning, and the troubleshooting methodology used to resolve them.

Index Terms—fault simulation; line relaying, distance protection, differential protection

I. Introduction

End-to-end testing is the process of applying time-synchronized fault simulations to protective relaying at each end of a transmission line in order to verify protection response. There are a multitude of ways to create end-to-end test procedures. This paper will focus on AEP's process for creating and implementing end-to-end test plans, as well as a methodology for troubleshooting to discover and solve various issues that can occur.

The end-to-end test plan is a collection of faults simulated at different locations on and near the transmission line protection under examination. AEP utilizes ASPEN software to simulate and obtain secondary fault values seen by each terminal's line relaying. The number of faults simulated varies depending on topology of the line tested, but the typical number is fourteen (line-to-line and line-to-ground faults at seven locations).

This fault data for each terminal is exported to an Excel file where pre-fault and post-fault conditions are prepended and appended, respectively. The pre-fault state consists of secondary voltage and current magnitudes each relay would see during "normal" conditions, for a duration long enough to overcome loss-of-potential logic. The post-fault state consists of normal secondary voltage and zero current in order to simulate the opening of the line breaker(s). The resulting data is exported into a Doble Protection Suite file.

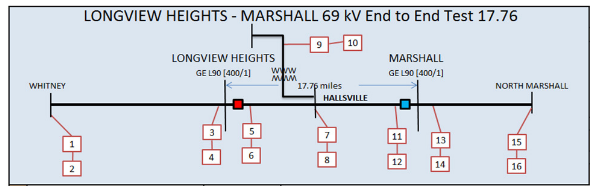

Fig. 1. AEP Oneline detailing location of simulated faults

Field personnel at each end are equipped with GPS-synchronized Doble F6150 test sets in order to run the created Protection Suite file. Once the sequence of faults is performed, field and/or engineering personnel examine the protection response to the simulation and determine whether it acceptably meets the protective intent of the system.

An effectively created end-to-end test plan takes a number of things into consideration. Fault simulation selection should not be limited to the protected line. The test plan should take into account any tap stations on the protected line, series elements, parallel lines, etc. Faults should also be placed behind each station, in order to verify whether reverse tripping operates as desired (or not desired).

AEP fault simulations are performed under two scenarios. The first is when any hi-speed communication-aided tripping scheme is disabled. The intent is to test for the proper operation of any backup elements (step distance, overcurrent, etc.). AEP refers to these tests as "no-comm" tests. Since these elements typically have a time delay, the fault state should have a longer duration in order to allow these elements to operate. AEP sets the fault duration for 120 cycles when testing backup elements. This testing is usually performed first in order to effectively find and resolve issues before synchronization with the remote end is required. Proper operation of these backup elements during testing can focus troubleshooting efforts on the communication scheme/setting should errors arise there.

The second scenario is with hi-speed communication scheme(s) in service. This is referred to as "comm" testing. AEP's typical fault duration is 10 cycles. This should be sufficient for most communication-aided relaying applications. Through the application of faults under both scenarios, this should provide an effective examination of relay element pickup selection, protection logic, and hi-speed relay communications.

II. Utilizing Relay Records

Microprocessor relays provide a number of resources for diagnosing problems found during this process. Relay oscillographs provide helpful analog and digital data. Analog data from the relay can be compared against the applied analog currents/potentials in the test plan in order to determine any irregularities.

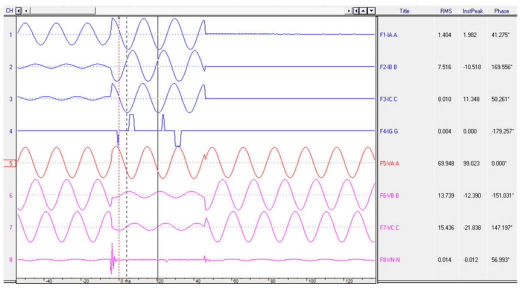

Fig. 2. Analog data derived from COMTRADE file

Digital elements can be examined in order to determine which element caused the relay to trip.

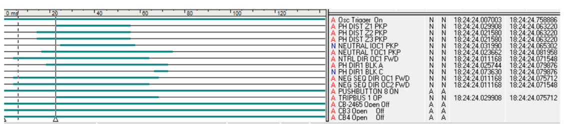

Fig. 3. Digital element data derived from COMTRADE file

Additionally, GPS synchronization of records obtained from each end is invaluable in assessing proper time-sync of fault application.

III. Considering Potential Sources Of Errors

Given the thorough system examination end-to-end testing provides, there are numerous potential sources for problems. Errors discovered during this process will exist in three possible places: the creation of the test plan, the relay settings, and/or the application of the test plan.

An improper or faulty model of the system can cause test plan creation errors. Incorrect CT/PT ratios for the modeled relays can also cause issues. Improper or incomplete information about neighboring utility infrastructure can also create problems.

Protective settings issues are often discovered using end-to-end testing. Typically, the settings are created using the same system model as the test plan, and an error there can propagate into test plan creation. For any communication scheme that relies on transmission/reception of digital signals, proper mapping of these elements must be verified. Protection schemes that rely on proper application of distance elements can have problems, such as the reverse blocking zone being out-reached by remote end pilot zone. Proper reach of forward-facing elements (especially zone 1) must be verified.

Field application of the test plan can also be prone to errors. Rolled polarity of leads, rolled phases, improper application of settings, faulty GPS sync, etc. can all impede proper end-to-end testing. These issues are most effectively identified utilizing relay records.

IV. Troubleshooting Process

In order to efficiently diagnose and correct problems discovered during the end-to-end process, a methodology must be established. The first step is to request event records from the field. The time the field will require to retrieve and send the events will provide an opportunity for the second step, which is to examine the created test plan for any errors. The test plan must be ruled out first as the source of any problems in the process, as this will provide for more effective downstream troubleshooting. Third, a re-examination of relay settings should occur. Only after the test plan and relay settings are verified as proper should examination be placed on the field application of the test plan. Utilizing the field-provided event data, a determination of proper test plan application can be obtained.

V. Errors In Test Plan Creation

Marconi - Laureles is a 138 kV transmission line with a hi-speed directional comparison blocking scheme (DCB) on System 1, and step distance elements on System 2. It is relevant to note that this line interconnects two different utilities, each having different implementations of protective relaying standards.

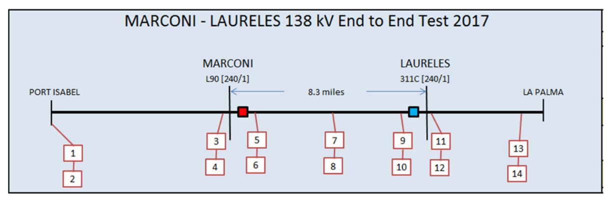

Fig. 4. Marconi – Laureles oneline and simulated fault locations

Field personnel performed no-comm testing on the System 1 relay with the results shown in Fig. 5. After no errors were found, performed the comm testing with similar success. They then moved onto the step distance System 2. An overreaching Z1 element at Laureles was discovered, as seen in Fig. 6.

	Test Name/Location	for Single-End
1.	A-G PORT ISABEL 138kV Bus	Trip,Neut TOC,AG 57.078 cyc
2.	B-C PORT ISABEL 138kV Bus	Trip, PH Dist Z2, BC, 61.572 cyc
3.	B-G 2% MARCONI - PORT ISABEL	Trip, Gnd Dist Z2, B G,31.566 cy
4.	A-C 2% MARCONI - PORT ISABEL	Trip, PH Dist Z4, AC PH, 31.512 cy
5.	C-G 2% MARCONI - LAURELES	Trip, Gnd Dist Z2, C G, 31.53 cy
6.	A-B 2% MARCONI - LAURELES	Trip, PH Dist Z4, AB, 31.41 cy
7.	A-B-C-G 50% MARCONI - LAURELES	Trip, PH DIST Z1,ABC PH, 1.176 cyc
8.	B-C-G 50% MARCONI - LAURELES	Trip, PH Dist Z1, BCG,1.254 cy
9.	A-G 98% MARCONI - LAURELES	Trip, Gnd Dist Z1, Neut IOC, AG, .99 cy
10.	B-C 98% MARCONI - LAURELES	Trip, PH Dist Z1, BC, 1.092 cy
11.	B-G 2% LAURELES - LA PALMA	noop
12.	A-C 2% LAURELES - LA PALMA	noop
13.	C-G 80% LAURELES - LA PALMA	noop
14.	A-B 80% LAURELES - LA PALMA	noop

Fig. 5. @Laureles System 1 – SEL 421 Results

	Test Name/Location	for Single-End
1.	A-G PORT ISABEL 138kV Bus	trip, time,AG,51, 56.136 cy
2.	B-C PORT ISABEL 138kV Bus	trip, BC,Z3, 61.71 cy
3.	B-G 2% MARCONI - PORT ISABEL	trip, BG, Z1, 1.632 cy
4.	A-C 2% MARCONI - PORT ISABEL	trip, AC, Z1, 1.758 cy
5.	C-G 2% MARCONI - LAURELES	trip, CG,Z1, 1.644 cy
6.	A-B 2% MARCONI - LAURELES	trip, AB,Z1,1.716 cy
7.	A-B-C-G 50% MARCONI - LAURELES	trip, ABC, Z1, 1.566 cy
8.	B-C-G 50% MARCONI - LAURELES	trip, BCG, Z1, 1.506 cy
9.	A-G 98% MARCONI - LAURELES	trip, AG, Z1, 1.38 cy
10.	B-C 98% MARCONI - LAURELES	trip, BC, Z1, 1.254 cy
11.	B-G 2% LAURELES - LA PALMA	noop
12.	A-C 2% LAURELES - LA PALMA	noop
13.	C-G 80% LAURELES - LA PALMA	noop
14.	A-B 80% LAURELES - LA PALMA	noop

Fig. 6. @Laureles System 2 – SEL 311C Results

Relay records were requested from the field while initial troubleshooting began. The test plan was examined for any errors, but was not the immediate suspicion of cause due to the successful results of System 1. While not completely ruling out the test plan, relay settings were examined.

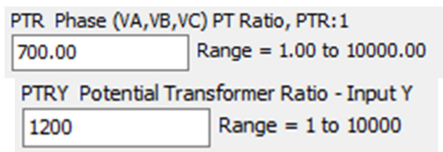

Fig. 7. @Laureles 311C PTR = 700, 421 PTR = 1200

A comparison of relay settings revealed a PT ratio difference between the System 2 relaying at Marconi and Laureles. The test plan was created assuming the PT ratio was set the same for both relays at both stations. The Laureles station-owned utility intentionally utilizes a different PT ratio on System 2 than System 1. This was an oversight by the Marconi-owned utility engineer when creating the test plan. Upon verifying the wired PT ratio of 700:1 with Laureles field personnel, the test plan was modified. The resulting re-test produced proper results and verification of protective settings effectiveness.

VI. Errors in Relay Settings

Kenedy SW – Helena 138kV is a transmission line with System 1 utilizing a permissive overreaching transfer trip (POTT) scheme over the Mirrored Bits protocol. Previously, the line had been Kenedy SW – Milton. Helena was constructed and implemented line protection. This required a modification of settings at the Kenedy SW end. It is important to note that Kenedy and Helena are owned by different utilities, with different implementation of relay standards.

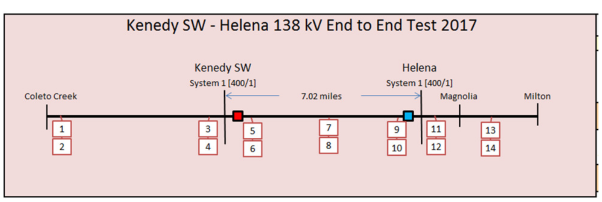

Fig. 8. Kenedy SW – Helena oneline and simulated fault locations

Field personnel at each end performed no-comm testing on System 1 and found no errors. Comm testing was then performed and identified issues at the Kenedy SW end. The POTT scheme at Kenedy SW was overreaching for phase faults, and not operating at all for ground faults.

	Test Name/Location	for End-to-End
1.	A-G 60% Kenedy SW - Coleto Creek	No-Op
2.	B-C 60% Kenedy SW - Coleto Creek	No-Op
3.	B-G 2% Kenedy SW - Coleto Creek	No-Op
4.	A-C 2% Kenedy SW - Coleto Creek	No-Op
5.	C-G 2% Kenedy SW - Helena	Trip,Gnd Dist Z1,Gnd Inst OC,C-G,0miles,0.96cyc
6.	A-B 2% Kenedy SW - Helena	Trip,A-B-PH Dist Z1,PH Inst OC,POTT,0.75cyc
7.	B-C-G 50% Kenedy SW - Helena	Trip,B-C-G,POTT,PH Dist Z1,0.936cyc
8.	A-B-C-G 50% Kenedy SW - Helena	Trip,A-B-C,PH Dist Z1,POTT,5.62miles,0.348cyc
9.	A-G 98% Helena - Kenedy SW	No-Op
10.	B-C 98% Helena - Kenedy SW	Trip,B-C,POTT,0.888cyc
11.	B-G 2% Helena - Milton	No-Op
12.	A-C 2% Helena - Milton	Trip,A-C,POTT,0.996cyc
13.	C-G 60% Helena - Milton	No-Op
14.	A-B 60% Helena - Milton	Trip,A-B,1.00cyc

Fig. 9. @Kenedy SW – Faulty comm results

	Test Name/Location	for Single-End
1.	A-G 60% Kenedy SW - Coleto Creek	No-Op
2.	B-C 60% Kenedy SW - Coleto Creek	No-Op
3.	B-G 2% Kenedy SW - Coleto Creek	No-Op
4.	A-C 2% Kenedy SW - Coleto Creek	No-Op
5.	C-G 2% Kenedy SW - Helena	Trip,C-G,Gnd Dist Z1,Gnd Inst OC,0.00miles,0.972cyc
6.	A-B 2% Kenedy SW - Helena	Trip,A-B,Ph Dist Z1,Ph Inst OC,DTT2 Trip,NoMiles,0.93cy
7.	B-C-G 50% Kenedy SW - Helena	Trip,B-C-G,PH Dist Z1,DTT2 Trip,NoMiles,0.93cyc
8.	A-B-C-G 50% Kenedy SW - Helena	Trip,A-B-C,PH Dist Z1, DTT2 Trip,3.51miles,0.84cyc
9.	A-G 98% Helena - Kenedy SW	Trip,A-G,Gnd Dist Z2,7.02miles,31.482cyc
10.	B-C 98% Helena - Kenedy SW	Trip,B-C,Ph Dist Z2,7.01miles,25.02cyc
11.	B-G 2% Helena - Milton	Trip,B-G,Gnd Dist Z2,7.02miles,31.302cyc
12.	A-C 2% Helena - Milton	Trip,A-C,Ph Dist Z2,7.01miles,25.392cyc
13.	C-G 60% Helena - Milton	Trip,C-G,Gnd Time OC,14.96miles,65.22cyc
14.	A-B 60% Helena - Milton	Trip,A-b,Ph Dist Z3,14.68miles,91.02cyc

Fig. 10. @Kenedy SW – Proper no-comm results

Relay records were requested from field personnel at both stations while re-examination of the test plan began. All CT and PT ratios were confirmed with field personnel to be correct, and the ASPEN model was examined and determined to be correct. This effectively ruled out the test plan as the cause of the errors.

This led to an examination of relay settings, and a reflection of the issues encountered in the context of the applied protection scheme. The overreach of the phase elements at Kenedy SW implied an issue with the permissive signal being properly transmitted/received. The absence of hi-speed ground tripping in the POTT scheme implied a logic issue. Relay settings were requested from field personnel at both ends.

An effective examination of the POTT scheme implementation meant identifying the means for transmitting and receiving mirrored bits at both ends.

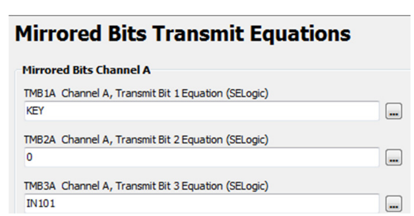

Fig. 11. @Helena – KEY element transmitting on Mirrored Bit 1A

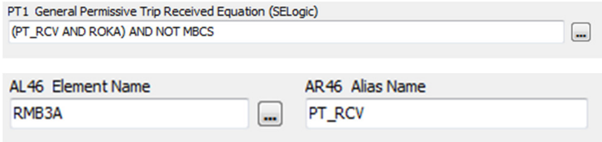

Fig. 12. @Kenedy SW – Receiving permissive on Mirrored Bit 3A

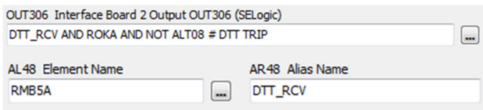

Fig. 13. @Kenedy SW – Receiving direct transfer trip on Mirrored Bit 5A

From an examination of the mirrored bit transmit/receive settings at each end, it was discovered that there was a mismatch in the permissive signal mirrored bit assignment. The discrepancy was discussed with Helena engineering personnel and subsequently resolved.

The issue of the POTT failure on ground faults pointed to an issue with the TRCOMM logic equation @Kenedy. The equation was set for the Zone 2 ground distance element.

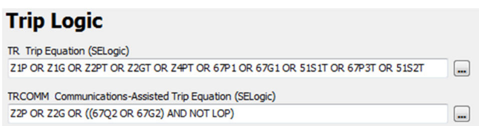

Fig. 14. @Kenedy SW – Z2P & Z2G in TRCOMM equation

Examining the ground distance settings showed this setting to be OFF. The Kenedy SW-owned utility opts to swap Z2 and Z4 elements as an inherited practice from limitations of earlier generations of SEL relays.

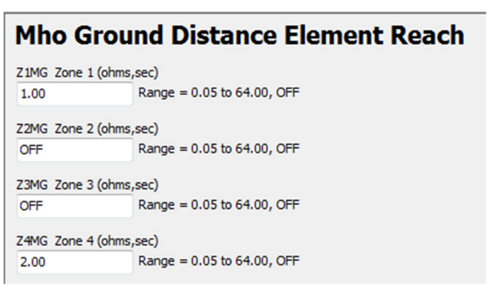

Fig. 15. @Kenedy SW – Z2MG set to OFF

Once the settings errors were corrected, the POTT scheme at Kenedy SW no longer overreached, and operated appropriately for ground faults on the protected line. This is an example of a multi-fold problem solved by this troubleshooting methodology.

VII. Errors In Test Plan Application

A. *Welsh - Monticello*

Field personnel were performing no-comm testing at Welsh for the Welsh - Monticello 345kV line. Results showed Zone 1 elements tripping instantaneously for reverse faults. AEP does not implement instantaneous Zone 1 tripping in the reverse direction.

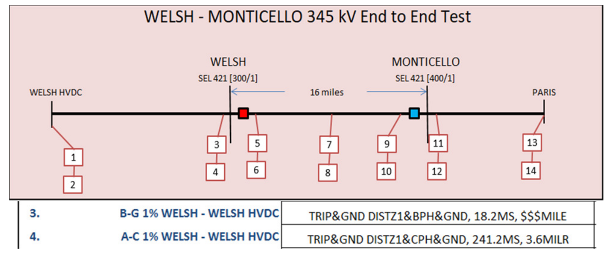

Fig. 16. Welsh – Monticello oneline, simulated fault locations, and no comm results

Relay records were requested from the field while the test plan was examined. All CT & PT ratios were verified to be correct. In ASPEN, mho circle response to fault playback was examined and confirmed that distance elements at Welsh were not supposed to operate for faults at locations 3 & 4. The application of distance zones is unusual in that there is no phase zone 1 element. However, this was confirmed with the settings engineer to be intentional.

Upon receiving relay records from the field, it was immediately apparent there was in issue with the applied currents.

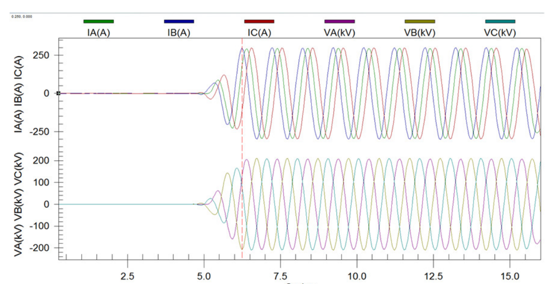

Fig. 17. @Welsh – Pre-fault state, currents not properly balanced

Opening the phasor component of the event file and comparing with the test plan applied currents, it was apparent there was a problem on the B and C-phase currents.

Channel	Mag	Angle	Scale	Show	Ref
IA(A)	300.0	-0.7	1	1	0
IB(A)	299.2	59.9	1	1	0
IC(A)	299.7	299.4	1	1	0
IG(A)	597.1	-0.5	1	0	0
VA(kV)	210.6	0.0	1	1	1
VB(kV)	210.7	240.0	1	1	0
VC(kV)	210.7	120.0	1	1	0

Fig. 18. @Welsh – Phasors with A-phase voltage reference

Figure 17 represents a snapshot of the event from the pre-fault portion of the fault on a primary value basis. Comparing the angles of the B and C phase currents to the applied current angles shows a 180 degree difference.

PREFAULT	mag	ang
VA	70.2	0.0
VB	70.2	-120.0
VC	70.2	120.0
TA	1.00	0.0
TB	1.00	-120.0
TC	1.00	120.0

Fig. 19. Test plan current & potential values applied to @Welsh relay

This implies a roll of test leads connected to the polarity and non-polarity relay current inputs. Field personnel reviewed test set connections and confirmed the roll on both B and C phase current leads. The connections were corrected, and proper results ensued.

B. North Edinburg – Mirasoles – Del Sol

A three terminal test was being performed between North Edinburg, Mirasoles, and Del Sol substations. The line was protected by three relay systems. System 1 and System 2 were fiber-connected current differential relays, and System 3 was a directional comparison blocking (DCB) scheme utilizing power line carrier.

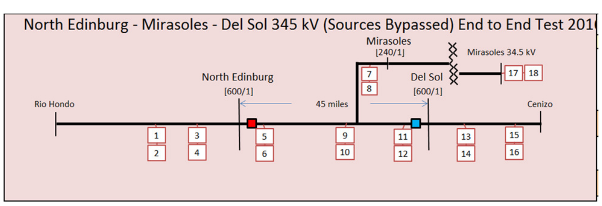

Fig. 20. North Edinburg – Mirasoles – Del Sol oneline and simulated fault locations

Testing began on the System 1 fiber current differential relaying. Field personnel elected to run communications testing before no-comm testing, and chose to start with faults behind each terminal. During testing, all three terminals tripped on differential for faults at locations 3, 14, 17.

Relay records were requested from each terminal while the test plan was examined for errors. CT and PT ratios specified in the test plan were verified to be correct for all three terminals. Relay settings were then examined for validity. In a fiber current differential scheme, it is critical to examine CT ratio settings not only at the local end, but the remote CT ratio tap settings as well. These were all confirmed to be correct.

Due to the relay records arriving at different times, each record was compared to the test plan applied currents as they were received. Comparing analog values confirmed that there were no rolled leads or improperly applied analogs at any of the three stations.

At this point, the test plan was confirmed not to have any errors, the settings were found to be correct, and relay records confirmed no errors in application by field personnel. Tests 3, 14, and 17 were run again to verify improper operation, and again tripped on differential. Since the test plan and settings were correct, efforts were focused on a yet un-explained cause in the field. With events from all three stations available, they were time-synced and examined for any irregularities.

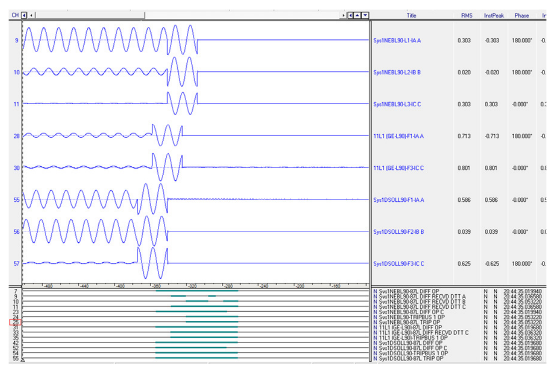

Fig. 21. Synchronized event files depicting each terminal transistioning to fault state at different times

The time-synced file reveals each station transitioning from the pre-fault state to the fault state at different times. This reveals the fact that the test sets were not properly synchronized with each other. Examination of the test set firmware at each end revealed mismatched versions. Once all three test sets were upgraded to the same firmware revision, the GPS synchronization was re-established, and field tests performed as expected.

VIII. Conclusion

End-to-end testing is an effective method of evaluating transmission line protection. The process not only evaluates protective relay settings, but also the protective intent of the relay logic, as well as the integrity of any communication channels utilized for high speed tripping.

End-to-end testing is often the last task to perform during projects that involve construction/upgrade of transmission lines. This is due to requiring all breakers, transmission lines, relay panels, communication paths, etc. to be constructed and tested first. This leaves personnel with a limited window at the end of the project before energization to not only perform end-to-end testing, but also solve any problems discovered during the process. The troubleshooting methodology detailed in this paper can be utilized to make best use of limited time to identify and correct errors in the end-to-end process. It allows for an efficient use of field and engineering personnel working in parallel to rectify testing issues, and contributes to the overall successful implementation of transmission line protective relaying.

IX. Biography

Jose R. Garza received his BS degree in electrical engineering from Texas A&M University Kingsville in 2009. He joined American Electric Power in May of 2009. He worked for three years as a protection and control technician. Since April 2012, he has held the position of protection and control Tech Support Engineer, currently holding the title of Senior Engineer. Jose is responsible for a variety of matters related to relay testing and troubleshooting, as well as construction project support and personnel training.