End-to-End Dynamic Testing Methodology for Validation of Line Differential Protection - Test Considerations and Challenges

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SUMMARY

The timing signals used for synchronization have a great influence on the results of End-to-End tests and now typical time sources like GPS-enabled clocks are not always available. The evolution of Precision Timing Protocol (PTP) and the universality of ethernet networks has made it even easier to access this kind of time source which can be reliably used for End-to-End tests in cases where other time sources are not available. However, there could be and will be situations when not all devices in a station support the IEEE 1588 v2 PTP. In this paper, the theory of line differential protection, the importance of end-to-end testing, test considerations, and validation of differential characteristics using dynamic tests to perform End-to-End tests are discussed. IRIG-B signals from GPS referenced clock as well as PTP network clocks are used to synchronize the test systems, and test results are compared. Specifically, the phase differential element (87L) is tested for accuracy, time of operation, and security by simulating internal faults for a short transmission line, and results are discussed. This paper proves that validation of line current differential by performing End-to-End tests using dynamic test methods successfully involving non PTP equipment as well as PTP equipment is achievable. This paper also sheds light on the challenges involved in end-to-end testing when using different models of test equipment with different signal processing times. Recommendations are provided on how to calculate the time differences in injection time between different test sets and how to overcome the challenges associated with the synchronization of such test sets, for simultaneous injection.

KEYWORDS

Line Differential Protection, IEEE 1588 PTP, End-to-End Testing, COMTRADE Playback, Injection Delay Time

INTRODUCTION

Line differential protection is one of the most popular applications used for transmission line protection. The line differential protection works on the theory of Kirchhoff's law where the magnitude of the current flowing into the line should be equal to the current flowing out of it. For line differential protection, the zone of protection is defined by the location of Current Transformers (CTs) monitoring the currents on either end of the transmission line. It is crucial for the protective relays on both end of the line to communicate with each other when a fault condition is established and issue a trip signal for the in-zone fault.

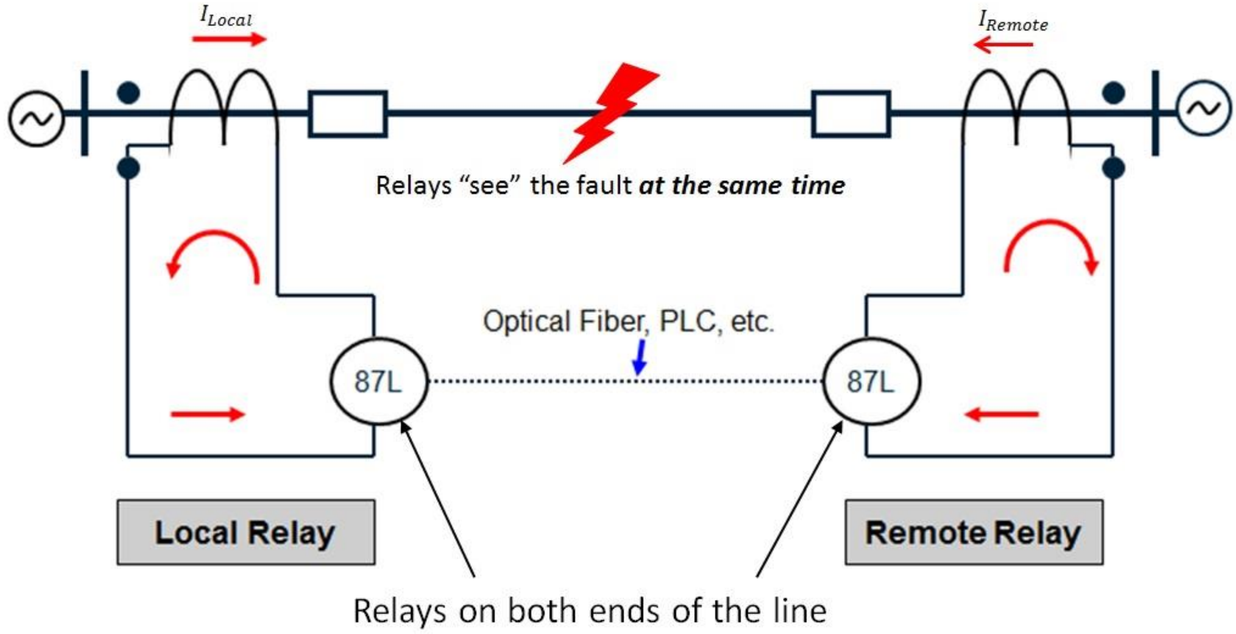

Figure 1 - Line Differential Protection

In *Figure 1*, a single line diagram shows the set-up of line current differential relays (87L) installed on either end of the transmission line. The relays monitor current from the CTs they are connected to, on both ends of the transmission line. These relays which are referred to as "Local" relay and "Remote" relay are connected to each other by means of optical fiber cables for the purpose of communication. When a fault occurs on the line, the relays see the fault at the same time. Based on the information received from the other end, the relays "decide" what needs to be done – Trip or Restrain.

There are different methods used by relay manufacturers to measure and compare currents in differential protection relays such as magnitude comparison, phasor comparison, phase comparison, charge comparison, or different combinations of these options. One of the popular methods used by a relay manufacturer is the alpha plane characteristic to determine line differential condition. This is further elaborated in the next section.

UNDERSTANDING ALPHA PLANE CHARACTERISTICS

The ratio of phase currents (or sequence currents) entering or leaving a transmission line is geometrically represented on a complex plane, which constitutes the alpha plane characteristics. Currents considered for the ratio calculation can be either monitored values of phase currents at remote and local relays or derived currents from calculations involving equations that use real and imaginary parts of differential and restrain currents obtained from monitored phase currents. Usage of these algorithms varies by relay models. In *Figure 2*, k represents the ratio of the currents. The area of stability and trip can be determined by the characteristic parameters due to which any percentage differential characteristics can be mapped onto the alpha plane. The restrain region is defined by parameters such as the radius of the greater arc (R), radius of the inner arc (1/R) and the angle (α). The radius of the greater arc and inner arc determines the radius of the restrain region (stability area) and the angle (α) represents the angular extent of the restrain region. Each phase has its own alpha plane characteristics. [1]

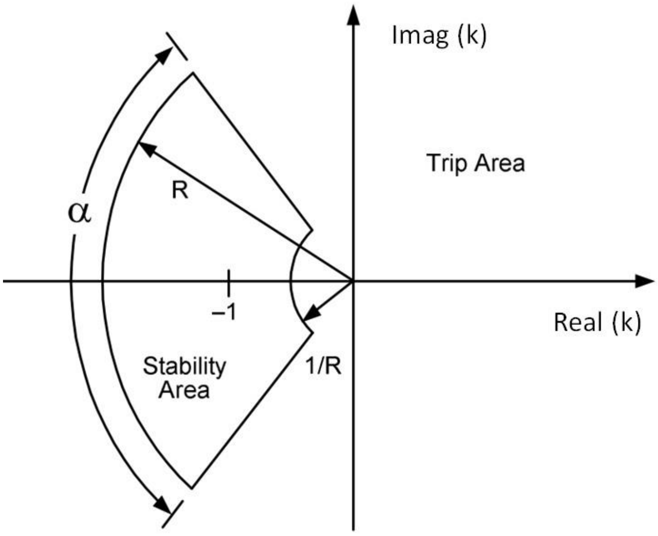

Figure 2 - Alpha Plane Characteristics

In the example, if the A phase current monitored by the local relay is $3\angle 0°$, then the remote relay will record $3\angle 180°$. The ratio of the remote current to local current would be:

$$\frac{\overrightarrow{IRemote}}{\overrightarrow{ILocal}} = \frac{3\angle 180°}{3\angle 0°} = 1\angle 180°$$

Equation 1 - Alpha plane ratio calculation

On the alpha plane, this ratio will plot on the real axis to the left of the imaginary axis. As could be seen in *Figure 2*, this falls in the restrain region, which is also the stability area. This case can be related to nominal load condition or an external fault depending on the current levels. In the case of an internal fault, the currents read by both the relays for their respective phases tend to be in phase with each other as they monitor the currents feeding the internal fault. This will plot the resultant of the ratio to be $0°$, which falls in the trip region of the alpha plane characteristics shown above.

END-TO-END TESTING

End-to-End testing is the evaluation of a relay protection scheme by simulating fault conditions simultaneously at each end of the transmission line. [2] The ability to synchronize the test systems on each end is paramount. This means, test quantities should be injected to all the relay terminals simultaneously. Line differential relays receive a set of currents from its own terminals and data of currents from remote relay by various means of communication modes. Since the relays send time stamped information packets to each other, even a slight slip up of the time during injection can incorrectly stamp the packets reaching the local and remote relays; that might cause incorrect or unintended operation. Hence, a time signal from Global Positioning System (GPS) clock is used to synchronize multiple test systems. Time signals are available in various standards such as 1 PPS (pulse per second), IRIG-B, PTP (Precision time protocol), etc. In this paper, IRIG-B time sync standard is considered for testing. End-to-End testing method requires multiple relay test equipment with the ability to decode IRIG-B signal to trigger injection of analog signals simultaneously. The IRIG-B signal that is obtained by a GPS Receiver via antenna is also provided to relays under test. This kind of testing is used to evaluate a new protection scheme during commissioning of a substation, troubleshoot malfunction of relays, verify the relay setting changes, etc. [2]

Equipment (hardware/software/accessories) required to perform end-to-end test are listed below –

i) Two Relay test sets (with ability to decode IRIG-B signal and perform end-to-end)
ii) GPS Receivers
iii) Co-axial cables (to connect between GPS Receiver and Relay Test Sets, Relays)
iv) Two computers (to drive the relay test sets at respective substations)
v) Communication medium for Testers
vi) Test software with pre-built test cases

Communication based protection schemes when implemented correctly will result in efficient and reliable protection of transmission lines as compared to numerous relays which cannot communicate with each other. It is simpler to test individual relays in a scheme, however, it's more effective to test entire scheme as a whole which not only validates the components but also the communication aspect of the scheme. Issues that can occur with communication based schemes can be detected by End-to-End testing.

TESTING

To validate the line differential protection, three test scenarios were setup. In the first scenario shown in *Figure 3*, GPS timing reference units were used on both ends for synchronization of test equipment as well as relays. In the second scenario (hybrid) as shown in *Figure 4*, GPS reference unit on one end and PTP network clock on the other end were used for synchronization. In the third scenario as shown in *Figure 5*, PTP network clocks were used on both ends for synchronization. A slave clock/converter was used in the test setup on ends that involved PTP network clock for extracting the time signal required for synchronization. Analog signals and relay output monitoring connections were made between test equipment and relay current terminals on respective ends. Direct fiber communication was used between the local relay and the remote relay. IRIG-B signal was used to synchronize test equipment as well as the relays under test. Simulation of internal fault on the line under consideration was performed for all three scenarios and trip times were recorded for each relay. A first set of tests was performed using state sequences which involved usage of pre-fault, fault, and post-fault states. A second set of tests was performed using COMTRADE playback method to validate the line differential protection.

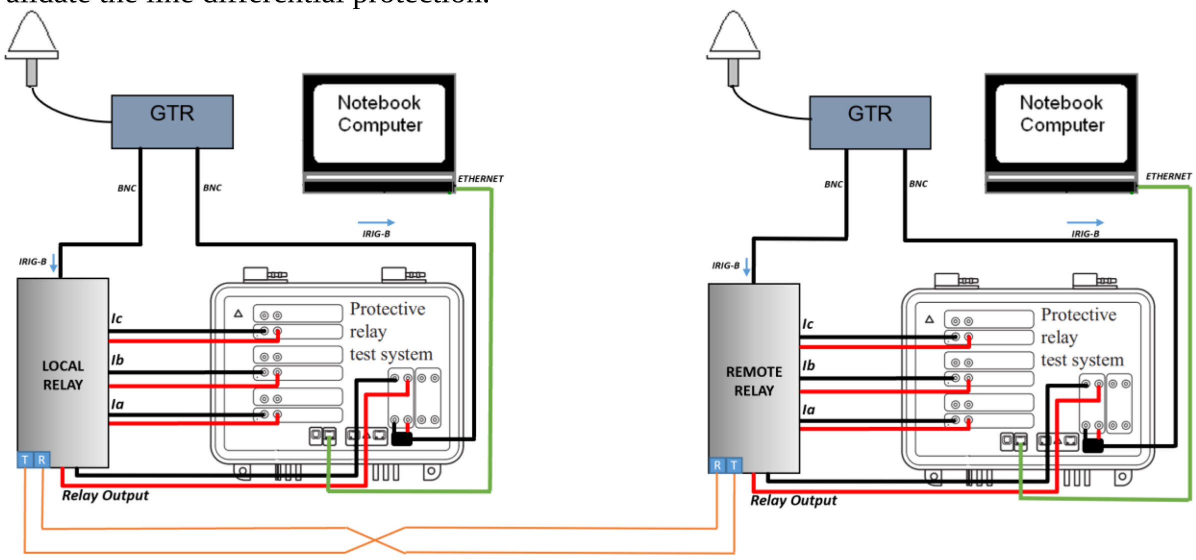

Figure 3 - End-to-End Test setup with GPS Timing Reference units on both ends

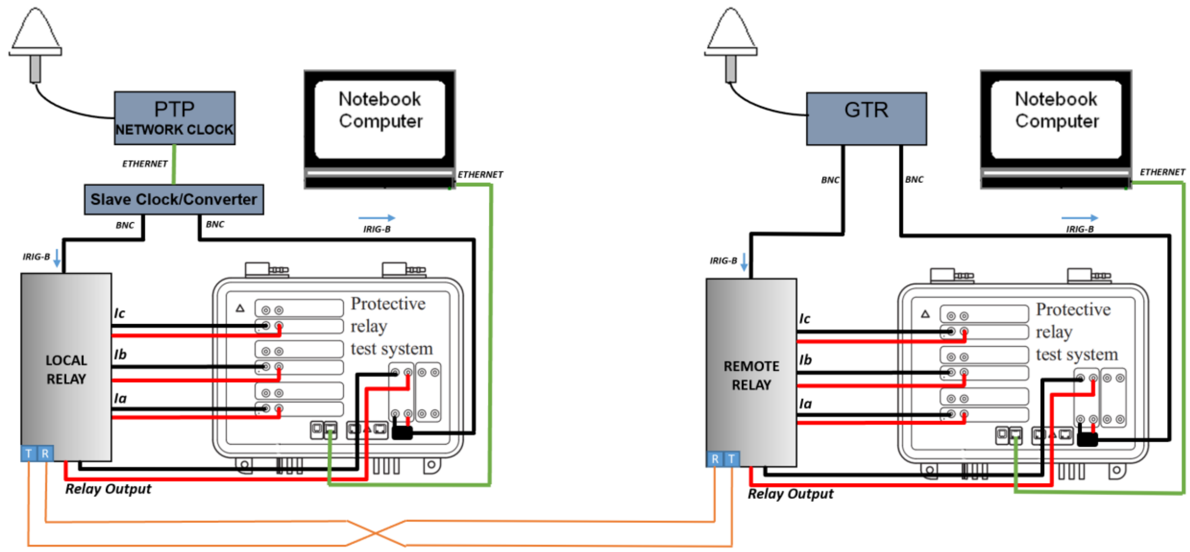

Figure 4 - End-to-End Test setup with GPS Timing Reference unit and PTP Network Clock (Hybrid)

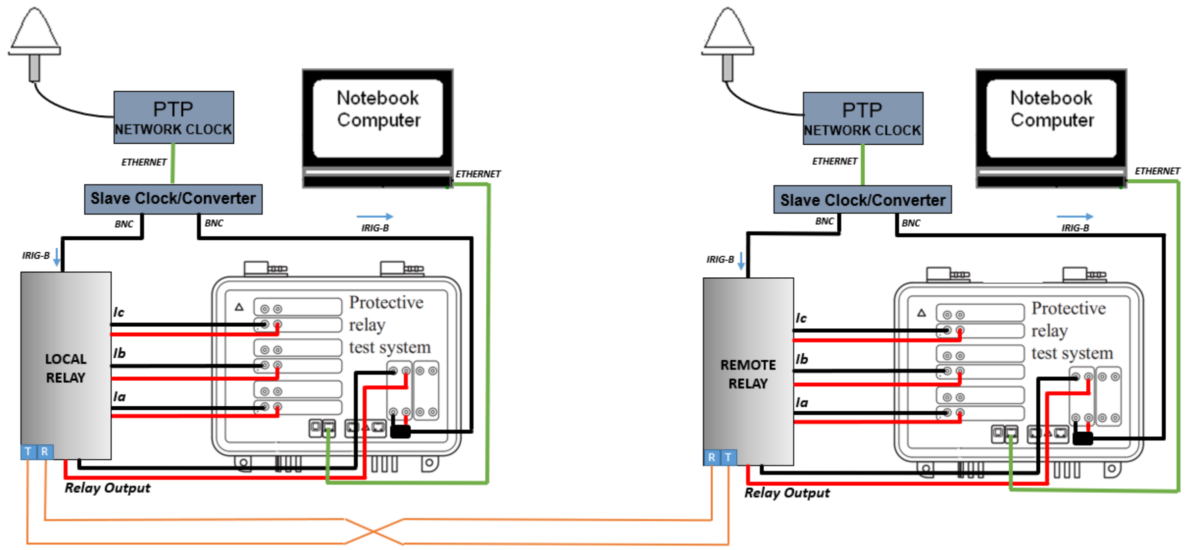

Figure 5 - End-to-End Test setup with PTP Network Clock on both ends

Setting	Local Relay	Remote Relay
CTR	1000	1000
Tap	5	5
Pickup	1.2 (in p.u)	1.2 (in p.u)

Table 1 - Protection Settings used for Testing

Settings shown in the *Table 1* were considered in local and remote relays for test purposes. The phase differential pickup setting is in per unit. Internal fault test was simulated on the relays with pre-fault, fault and post-fault states configured to validate the line differential protection. An initial state was configured, prior to prefault state, for the test equipment on both ends to be synchronized with the IRIG-B signal. *Table 2* shows the different states and test values used for the internal fault test.

	Pre-Fault State		Fault State		Post-Fault State	
	Local	Remote	Local	Remote	Local	Remote
Phase A	1∠0°	1∠180°	7.5∠0°	7.5∠0°	0∠0°	0∠180°
Phase B	1∠-120°	1∠60°	7.5∠-120°	7.5∠-120°	0∠-120°	0∠60°
Phase C	1∠120°	1∠-60°	7.5∠120°	7.5∠120°	0∠120°	0∠-60°

Table 2 - Test Values for Internal Fault Test

TEST RESULTS & ANALYSIS

Table 3 shows the trip times for local and remote relays for each scenario for tests performed using the state sequence method. L and R stands for local and remote relays respectively in the results table. The trip times are just under one and half cycles for all the scenarios as expected for operation of a line current differential protection for an internal fault on the line. It can be observed that the trip times are the same for both relays for the first scenario where both ends have GPS units. For scenarios two and three which involve PTP network clock in at least one of the ends, the local relay trips faster by one ms when compared to the remote relay which is still an insignificant difference.

Scenarios (State Sequence)	Local Relay Trip Time (ms)	Remote Relay Trip Time (ms)
1 - GPS units on both (L&R)	0.023	0.023
2 - GPS unit (L) – PTP (R)	0.022	0.023
3 - PTP on both (L & R)	0.022	0.023

Table 3 - Trip Times for State Sequence Method

To validate the line current differential using a second dynamic test method, the line was modelled in a digital simulation software and an internal fault was simulated on the line. COMTRADE files were generated by the digital simulation software which were then synchronously played back to both local and remote relays. The resulting trip times are shown in the *Table 4* below for the COMTRADE playback method. As observed from the table below, the test results are similar between local and remote relays with a difference of one ms between them.

Scenarios (COMTRADE)	Local Relay Trip Time (ms)	Remote Relay Trip Time (ms)
1 - GPS units on both (L&R)	0.037	0.036
2 - GPS unit (L) – PTP (R)	0.037	0.038
3 - PTP on both (L & R)	0.037	0.037

Table 4 - Trip Times for COMTRADE Playback Method

The test results confirm that the line differential protection implementation which involves non-PTP equipment/devices can be successfully validated using PTP network clock for synchronization of all test equipment involved as well as with a combination of conventional GPS reference clocks and PTP clocks. Test results of a conventional setup without using PTP network clock were compared to the setup that involved usage of PTP network clocks on both ends as well as to the hybrid setup. Alpha plane plot for one of the test scenarios is shown in the *Figure 6* where it shows the path of the test plot from restrain region to the operate region on alpha plane.

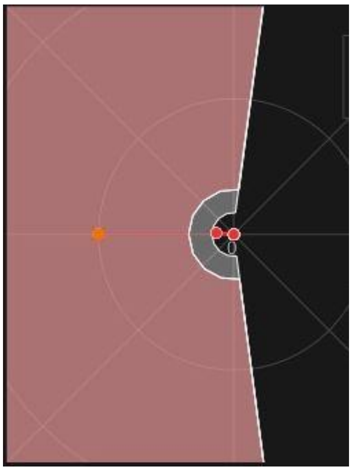

Figure 6 - Alpha Plane for Internal Fault Test

TEST CHALLENGES

There are many challenges when performing end-to-end testing which are already well explored in many papers [2][4]. One of the main challenges when testing using PTP network clock is the compatibility of test equipment with IEEE 1588 v2 PTP. In this paper, test equipment which could not be used directly with PTP clocks were used for validation of 87L. Since this paper explores different scenarios involving a combination of GPS units as well as PTP clocks, it opens up the challenge of synchronization of test systems which are not compatible with PTP. To overcome this barrier, a slave clock was used in the test setup that involved PTP clocks. This slave clock would be synchronized with the PTP master clock and also act as a converter to be able to provide the necessary IRIG-B signals for synchronization of test equipment as well as the relays involved.

Another challenge is the ability of test equipment on both ends to synchronize efficiently for successful end-to-end testing. This can become a bigger challenge when the test equipment on both ends are of different models or from different vendors. This means that the time that is taken by the test equipment to inject the analog signal from the time of initiation is different for each. To overcome this, it is essential to know how much time difference the test equipment have between them post trigger. To get this information a test setup as shown in *Figure 7* can be used. [3]

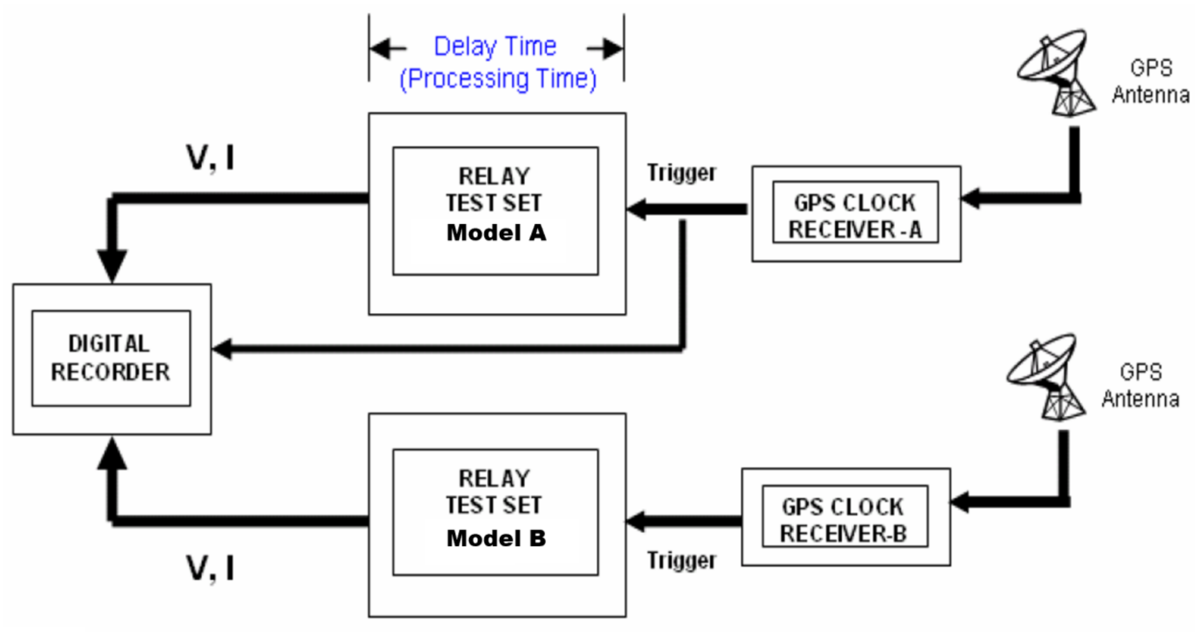

Figure 7 - Test Setup to measure Delay Time [3]

Analog signals from both test sets are connected to an oscilloscope. The trigger signal obtained from a GPS clock via antenna, used as reference, is also connected to the oscilloscope. Once the test sets receive the trigger pulse, the analog signals are injected to the oscilloscope. Processing time for each equipment is measured between post trigger time and the initiation of the signal [3]. The difference between processing time between two test sets could be called as compensation time or delay time. This is the delay or compensation used to ensure both test sets inject synchronously. *Table 5* below shows the measured delay time between two different models of test sets.

Equipment 1	Processing Time 1	Equipment 2	Processing Time 2	Delayed Test Set	Delay Time
Model A	23.7 ms	Model B	380 µs	Model B	23.32 ms

Table 5 - Injection Delay Times

CONCLUSION

Since line differential protection has been implemented all over the world by vast majority of utilities, it is significant to validate such protection schemes for their accurate operation for different fault conditions. End-to-End testing validates the entire communication based protection scheme including the operation of relays, as well as the communication between the relays. One of the prime factors for end-to-end testing is proper synchronization of devices involved in the test setup. The evolution of time sources over the years has led to the development of Precision Timing Protocol which brings in time information to the ethernet network. Since, PTP is known to be very accurate and also supports redundancy, it would not be a surprise if all future installations end up predominantly using PTP. There are many substations across the world that use legacy devices and systems that do not support PTP yet. This indicates that there will be situations which involve hybrids of legacy systems as well as PTP supported devices in the same substation. This not only poses challenges to the design and installation of such systems, but also to the testing of such protection systems with accurate results. Just like legacy devices in a substation, there are legacy test equipment and non PTP test equipment out there which are used even today for all kinds of protection testing. This paper proves that validation of such protection systems, specifically line current differential protection using end-to-end testing can be performed successfully with certain necessary tweaks to the conventional testing technique. An important factor to consider when testing such systems, is to make use of a slave clock, that has the ability to synchronize with a PTP master clock as well as act as a converter that provides the necessary time reference signals for synchronization of devices. Both state sequence and COMTRADE playback dynamic tests were performed; and their results compared to validate the equivalence between conventional test setup, PTP-only test setup and the hybrid test setup.

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