Cloud-Based End-to-End Testing of Protection Schemes.

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***Abstract*—End-to-end testing is performed to validate protection schemes for transmission lines. These tests are performed by injecting the test values at the relay terminals on both sides of the line under the test. The test magnitudes should be injected synchronously to simulate the system conditions during the fault properly. Traditional end-to-end testing requires the ability to actively control the generation of test signals on both ends of the line under test, requiring a highly skilled operator at each end.**

This paper presents a cloud-based approach for end-to-end testing of transmission line protection schemes like POTT & PUTT schemes. This test method controls the whole test from only one end of the line which provides more flexibility to the software used during the test, allowing for comprehensive pickup and timing tests along the full characteristic of the protection scheme and the automation of tests for these communication-based protection schemes. The approach is also less prone to operational errors since all configuration and loading of test cases is done from only one end. Test sets are connected to a cloud server managed by either the test set manufacturer, the testing company, or the asset owner. GPS-based IRIG-B timing reference is used for synchronization during the test. A battery of tests including stabilization verification, internal and external faults, and static and dynamic tests using state sequences are performed, and their results are compared with others obtained during traditional testing.

I. INTRODUCTION

Teleprotection systems are important for the integrity and reliability of electrical power networks, safeguarding the continuity and quality of power supply. These systems are designed to detect and isolate electrical faults with high speed and precision, ensuring the stability of the power grid and the safety of both infrastructure and personnel. By executing rapid disconnections of faulted segments, teleprotection schemes prevent the escalation of faults, thereby mitigating potential damage to equipment and reducing the risk of widespread power outages (Anderson & LeReverend, 2014).

The essence of teleprotection lies in its ability to communicate critical protection signals between substations across vast distances, leveraging a network of advanced communication technologies. This allows for a coordinated response to disturbances, enhancing the protection mechanisms beyond the capabilities of conventional, localized relay protections (Blackburn & Domin, 2020).

II. OVERVIEW OF TELEPROTECTION SCHEMES

Teleprotection involves the coordinated operation of protective relays positioned in different locations across the electrical grid.

The evolution of teleprotection schemes has been closely tied to advancements in communication technologies, transitioning from basic telegraph wires to sophisticated digital communication channels, including fiber optics and wireless links. This evolution has significantly enhanced the speed, reliability, and functionality of teleprotection systems, enabling real-time, high-speed communication between distant relays (Ziegler, 2011).

POTT and PUTT

Although many different types of pilot protection schemes exist, the present paper focuses on testing two directional comparison schemes known as POTT and PUTT schemes.

Permissive Under-Reach Transfer Trip (PUTT): The logic diagram for a PUTT scheme is shown in Figure 1 below. PUTT schemes use both underreaching (Z1A and Z1B) and overreaching (Z2A and Z2B) elements. Each terminal will trip directly for its underreaching element, and the permissive signal sent accelerates the tripping of the other end's overreaching element.

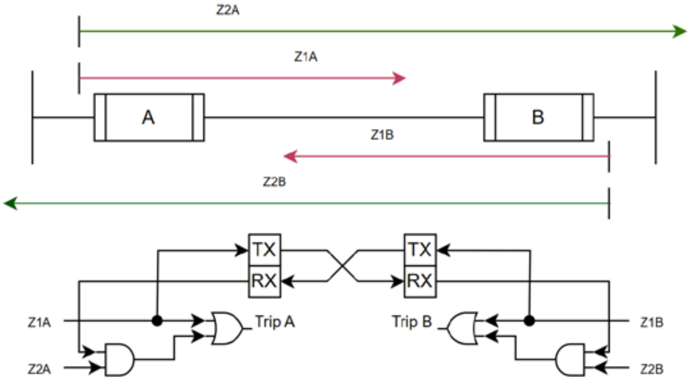


Figure 1 Logic Diagram for PUTT Scheme

Permissive Over-Reach Transfer Trip (POTT): The Permissive Overreach Transfer Trip (POTT) scheme employs a direct overreach component, indicated by Zone 2 shown in the simplified logic depicted in Figure 2, to transmit a permissive trip signal to the relay positioned at the distant end via the transmission communication channel (TX). Suppose the distant end's relay receives the permissive trip signal through the receiver communication channel (RX) and its second zone overreach element has identified a fault. In that case, it sends a command to open the circuit breaker.

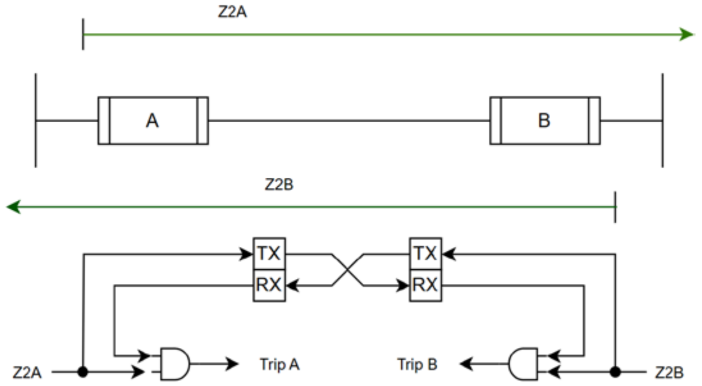


Figure 2 Logic Diagram for POTT Scheme

Table 1 POTT vs PUTT

Feature	POTT	PUTT
Tripping philosophy	Overreaching	Underreaching
Protected zone	Beyond Zone 1	Within Zone 1
Application	High-speed tripping between substations	Fault isolation within substations
Advantages	Faster tripping, improved system stability	Improved selectivity, avoids cascading outages
Disadvantages	Sensitive to infeed, the potential for misoperation	Limited protection range, slower than POTT for faults outside Zone 1

Communication Technologies

Teleprotection schemes use a wide range of communication technologies to link protective relays across the grid. These technologies range from dedicated pilot wire circuits to modern digital communication networks, including satellite links and internet-based protocols. The choice of communication medium is critical, influencing the speed, reliability, and security of the teleprotection scheme. Recent trends favor digital communication solutions for their bandwidth efficiency, scalability, and enhanced security features, which are vital for the protection of critical infrastructure (Miroslav M. Begovic, 2012).

III. CURRENT TESTING METHODS AND STANDARDS

Testing these schemes is crucial to ensure their reliability and effectiveness. The current methodologies for testing teleprotection schemes in transmission lines can be broadly classified into hardware-based, software-based, and statistical evaluation methods. Each of these methods provides a different approach to validating the schemes' performance under various conditions. This involves a comprehensive assessment of both the hardware components, such as relays and communication equipment and the software algorithms that govern decision-making processes.

Testing Facilities and Procedures

Advanced testing facilities can be used in the development and certification of teleprotection schemes. These facilities are equipped with sophisticated simulation equipment capable of replicating the electrical and operational characteristics of power systems, allowing for an exhaustive evaluation of teleprotection schemes under controlled conditions.

The testing process encompasses several key objectives, including the verification of correct operation, assessment of compatibility with existing power system infrastructure, and evaluation of the impact on system reliability and stability. Specific procedures involve:

1. **Simulation of Fault Conditions:** Creating realistic fault scenarios to assess the tele-protection scheme's response accuracy and timing.
2. **Communication Link Evaluation:** Testing the performance and reliability of the communication links under various conditions, including interference and signal degradation.
3. **Interoperability Testing:** Ensuring that teleprotection components from different manufacturers can operate seamlessly together, maintaining system integrity.
4. **Impact Analysis:** Assessing the teleprotection scheme's influence on the overall power system, particularly in terms of stability and operational efficiency.

In ensuring the stability and reliability of power transmission systems, teleprotection schemes serve a critical role by facilitating rapid fault detection and clearance. The rigor of their testing methodologies is of paramount importance, drawing from hardware-based simulations, software-driven models, and in-depth statistical evaluations. Herein, we detail these methodologies and provide references to substantiate their application and effectiveness.

Hardware-Based Testing Methods:

Real-Time Digital Simulators (RTDS): RTDS systems replicate power systems and telecommunication operations in real time, providing a dynamic testing environment. They are particularly valuable for analyzing the impact of communication channel impairments on teleprotection schemes.

RTDS's effectiveness is well-documented, with applications including the analysis of teleprotection schemes under suboptimal telecommunication conditions, highlighting their utility in simulating real-world scenarios (Rahman et al., 2018)

Hardware Test Boxes: Hardware test boxes are employed for their ability to emulate electrical signals and communication protocols relevant to teleprotection, providing a tangible assessment of scheme performance.

Such test boxes have been successfully used to validate teleprotection schemes, demonstrating their effectiveness in real-world applications. (Kuber & Gonzalez, 2022)

Software-Based Testing Methods:

Computational Platforms (MATLAB/Simulink, ATP, CAPE): Computational platforms are used to model and assess teleprotection schemes and allow for exhaustive testing under various simulated conditions.

These platforms have been leveraged to validate new teleprotection schemes, with CAPE software specifically recognized for its provision of realistic relay models, which facilitates comprehensive testing (Meira et al., 2021)

Probabilistic Methods (Monte Carlo Simulations): Probabilistic methods such as Monte Carlo simulations are implemented to appraise teleprotection performance, accounting for uncertainties in system behaviors and the stochastic nature of faults.

Monte Carlo simulations have provided a robust framework for performance assessment, enabling a probabilistic approach to the evaluation of teleprotection schemes (Santos et al., 2015).

Statistical Performance Comparison:

Markov Models and Figures of Merit: Markov models are employed to quantify the probability of teleprotection misoperations. These statistical measures are used to determine the schemes' reliability.

The application of Markov models has been used in statistically comparing teleprotection schemes, providing quantifiable metrics on their performance and reliability (Schweitzer & Kumm, 1998)

Comparative and Practical Assessments:

Comparative Studies: Comparative assessments using computer simulations are integral to testing teleprotection schemes, with studies showing that DCB schemes generally outperform POTT schemes in terms of operational speed and reduced delays, which are essential for preventing system instability (Meira et al., 2021)

Fault Simulations: Simulated faults are essential to testing the schemes' response, and ensuring they operate as designed under realistic conditions.

Simulations of various fault scenarios have demonstrated the efficacy of teleprotection schemes in eliminating faults expediently, underscoring their performance and efficiency (Meira et al., 2021)

These diverse methodologies confirm the multifaceted approach employed to validate teleprotection schemes, ensuring their robustness and efficacy. The references cited provide a comprehensive overview of the testing procedures and underscore the importance of continuous methodological enhancement to keep pace with the evolving demands of modern power systems.

IV. CLOUD BASED METHOD

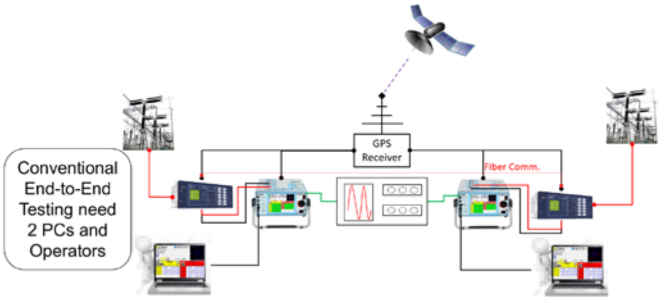


Figure 3 Conventional End-to-End Testing

Figure 3 illustrates a conventional method employed in the end-to-end testing of line protection relays, a fundamental aspect of teleprotection in power systems. As depicted in Figure 3 this testing setup involves two test sets placed at either end of the power line, which are connected to the relays responsible for the line protection. These test sets are integral to the process, as they are equipped to inject voltage and current signals into the system to simulate fault conditions, prompting the operation of the relays. In this configuration, two relays are interfaced with the test sets. The system's intricacy requires precise coordination between the local and remote ends to accurately replicate a fault scenario. This coordination is achieved through a GPS-based synchronization system, ensuring that the simulated faults are injected in a temporally coordinated manner, mirroring the conditions that would trigger teleprotection mechanisms during an actual fault.

Upon simulation of these faults, teleprotection signals are transmitted between the relays on both sides of the line. These signals carry vital information regarding the fault conditions, enabling the relays to make informed decisions on whether to operate. The operation of the relays is contingent on the specific protection scheme they are programmed to follow. These schemes dictate the conditions under which a relay should trip, clear a fault, or communicate with its counterpart at the other end of the line.

The infrastructure supporting this conventional testing method is comprehensive, necessitating the use of fiber-optic communication links for the high-speed transfer of teleprotection signals. This communication medium is illustrated as 'Fiber Comm.' in the image, indicating the role of fiber optics in providing a reliable and efficient channel for crucial data exchange between protective devices. Additionally, the setup requires the expertise of operators who manage the test sets, which are represented as PCs in the image. The requirement for two operators — one at each end of the line — underscores the complex nature of traditional end-to-end testing methods, necessitating a coordinated effort to ensure the integrity and success of the testing procedure.

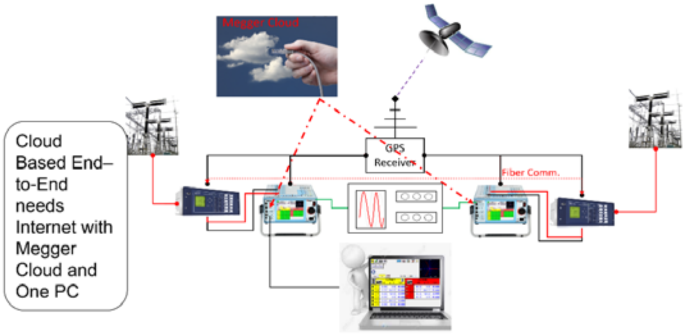


Figure 4 Cloud-Based End-to-End Testing

In cloud-based teleprotection testing methods, a streamlined and interconnected approach is utilized, as depicted in Figure 4 The testing infrastructure integrates local and remote test sets through cloud technology, enabling a more efficient and centralized testing process.

The process begins with connecting the test sets from each end of the power line to a cloud server. This server acts as a central hub, enabling the synchronization of test procedures and the sharing of data in real time. The cloud platform, shown in the diagram, serves as the element that facilitates the remote control of test equipment. It ensures that the commands and signals are consistently aligned, leveraging the robust synchronization capabilities provided by GPS technology.

Thanks to the cloud-based system's enhanced connectivity, operators can initiate and control the injection of voltage and current into the line protection relays from a single PC. This singular control point simplifies the coordination tasks. The cloud system's centralized nature also reduces the likelihood of human error and improves the accuracy of the fault simulation process.

When the testing begins, a coordinated fault is simulated between the local and remote ends. This fault is accurately synchronized with the timing signal used, e.g. POP or IRIG-B, to ensure that both the local and remote relays experience simulated fault conditions simultaneously. As these signals are transmitted through the cloud, the teleprotection relays on both sides receive the fault indicators. The relay's reaction, such as tripping or blocking, depending on the specific protection scheme being tested, is monitored, and recorded.

The fiber communication links depicted in the image are vital for the high-speed transmission of data between the cloud server and the protective relays. They ensure that the simulated signals and teleprotection commands experience minimal latency, which is crucial for the authenticity of the test results.

By utilizing cloud technology, teleprotection testing becomes more versatile and accessible, with the ability to control and execute tests from remote locations, provided there is internet connectivity. This not only streamlines the testing process but also offers the potential for automated testing procedures, real-time monitoring, and data analysis, which can be conducted from virtually anywhere, improving the overall efficiency and reliability of the power system's protective schemes.

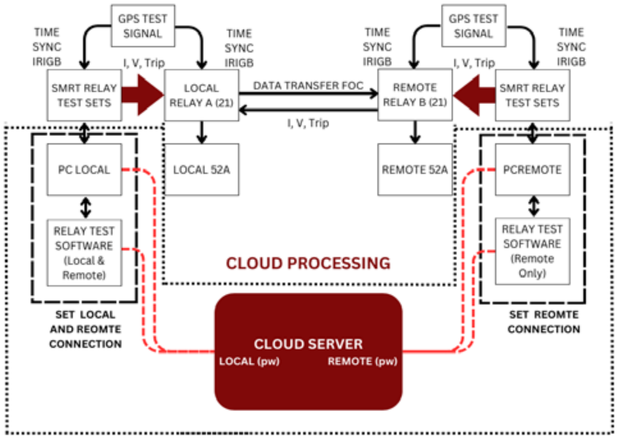


Figure 5 Cloud processing logic diagram.

In the depicted cloud-based teleprotection testing setup, the cloud server is the central node that facilitates and secures communication between the testing endpoints. The process initiates with the remote user connecting their test set to the cloud server, typically through a platform like Megger Cloud, designating the connection for remote operation. Simultaneously, the user at the local end connects their test set to the same cloud server, but with permissions set to control both the local and remote testing processes.

The cloud servers carry out a verification process where they compare the credentials, such as passwords, input by users on both ends. Upon successfully validating that the entered passwords match, the cloud server establishes a secure connection between the two test sets. This verification ensures that only authorized personnel can control the testing procedure, which is crucial for maintaining the integrity and security of the testing process.

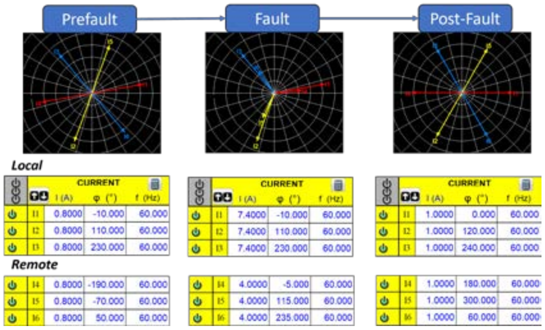
Once the secure connection is confirmed, the user from the local end gains the ability to control both test sets. This is made possible by the cloud processing mechanism which aligns the operations of both the local and remote test sets. It allows for synchronized injections of fault simulations into the power system's protective relays, coordinated through GPS signals to ensure precise timing.

This architecture offers enhanced flexibility and control, as operators can seamlessly switch commands between the local and remote sides without complications. The relay test software installed on the PCs at both ends provides the interface through which the operator manages the testing procedures, with the software at the local PC configured to handle both local and remote operations, while the software at the remote PC is set for remote operations only.

Moreover, the cloud-based method streamlines the testing procedure by negating the need for physical presence at both ends, as was necessary in conventional methods. The GPS synchronization, coupled with cloud processing, ensures that the timing of the fault events is perfectly coordinated, allowing the teleprotection schemes to be tested under realistic and controlled conditions that mimic actual fault scenarios in the power system.

V. TEST CONSIDERATIONS

To test line protection schemes such as POTT and PUTT, End-to-End testing is used. When using a state Sequencer tool, different power system faults are calculated and then injected into the local and remote relays using a sequence of power system states for each. Faults are simulated in different places along the line and with different load conditions. The most common method injects a prefault, fault, and postfault state for each test as can be seen in Figure 6 below. Modern test equipment configuration software allows for the injection of hundreds of these states. However, the time synchronization requirements of End-to-End tests limit the actual number of states that should be injected for each test.



Local

	CURRENT I (A)	φ (°)	f (Hz)		CURRENT I (A)	φ (°)	f (Hz)		CURRENT I (A)	φ (°)	f (Hz)
I1	0.8000	-10.000	60.000	I1	7.4000	-10.000	60.000	I1	1.0000	0.000	60.000
I2	0.8000	110.000	60.000	I2	7.4000	110.000	60.000	I2	1.0000	120.000	60.000
I3	0.8000	230.000	60.000	I3	7.4000	230.000	60.000	I3	1.0000	240.000	60.000

Remote

I4	0.8000	-190.000	60.000	I4	4.0000	-5.000	60.000	I4	1.0000	180.000	60.000
I5	0.8000	-70.000	60.000	I5	4.0000	115.000	60.000	I5	1.0000	300.000	60.000
I6	0.8000	50.000	60.000	I6	4.0000	235.000	60.000	I6	1.0000	60.000	60.000

Figure 6 Sequence of States from a Sequencer Tool

VI. TEST SETUP

The testing of the POTT and PUTT schemes was divided into two parts.

The first part of the tests was performed using the traditional method where two test sets are operated by two users, who communicate and start the tests using old feasible methods like mobile phones.

The connections shown in Figure 7 were used for this method.

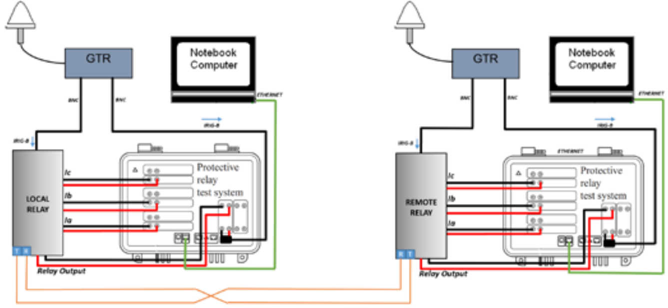


Figure 7 Traditional End-to-End Connections.

The second part of the tests was performed using the Cloud Based End-to-End Testing method, where two test sets are operated by one user using cloud server communication to start the tests.
The wiring connections shown in Figure 8 were used for this method.

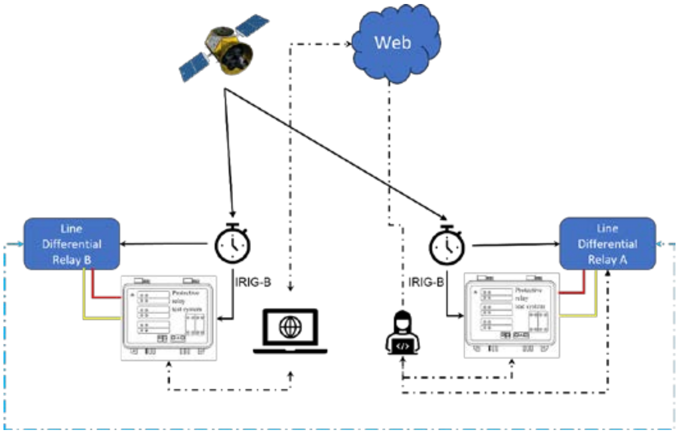


Figure 8 Cloud-Based Connections

The test set provided the voltage and current to the relay. The relay provides a breaker trip coil signal from an output contact that is hooked to a binary input of the test set.
Both Test sets and the relays were time synchronized using IRIG. The test sets simulated AB fault conditions in Zones 1 and 2 of each relay.
The simulated fault conditions were as follows:

a. Relay A fault at 10% of line and Relay B Fault at 90% of line.
b. Relay A fault at 90% of line and Relay B Fault at 10% of line.

Test sequences of three states as those shown in Figure 6 were used to perform these tests.
The first state starts by triggering the IRIG to synchronize both test sets, followed by starting a pre-fault injection; the second one is the fault condition state, and the third one is the END state.
The breaker contact is monitored in state two.

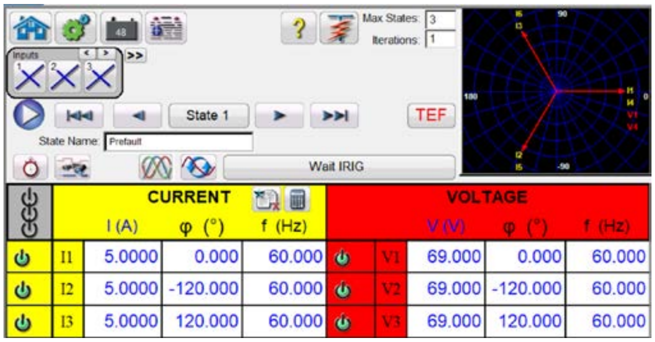
VII. RESULTS, COMPARISON & ANALYSIS

Four different tests were performed to validate the schemes in both the Traditional and the cloud-based methods. Each test was run five times, and an average time result was gathered.
The tests were as follows:

1. POTT - AB Fault at 10% of line in Zone 2 of Relay A and Zone 2 of Relay B.
2. POTT - AB Fault at 90% of line in Zone 2 of Relay A and Zone 2 of Relay B.
3. PUTT - AB Fault at 10% of line in Zone 1 of Relay A and Zone 2 of Relay B
4. PUTT - AB Fault at 90% of line in Zone 2 of Relay A and Zone 1 of Relay B

Unlike the PUTT scheme where the Zone 1 distance element was expected to operate on both relays for all faults located in Zone 1, In the POTT scheme, the Zone 2 distance element is used only to pick up, as the reach of Zone 2 includes Zone 1.
Figures 8 – 11 below depict the Traditional Testing State Sequence at 90% of the local and 10% of the remote ends of the line.

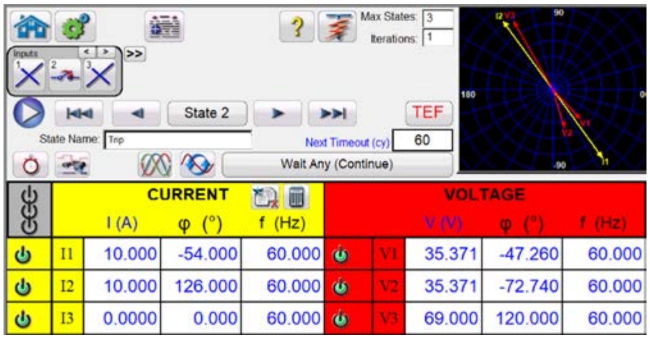
A. Traditional Testing POTT



Max States: 3
Iterations: 1
State Name: Prefault
Wait IRIG

	CURRENT				VOLTAGE		
	I (A)	φ (°)	f (Hz)		V (V)	φ (°)	f (Hz)
I1	5.0000	0.000	60.000	V1	69.000	0.000	60.000
I2	5.0000	-120.000	60.000	V2	69.000	-120.000	60.000
I3	5.0000	120.000	60.000	V3	69.000	120.000	60.000

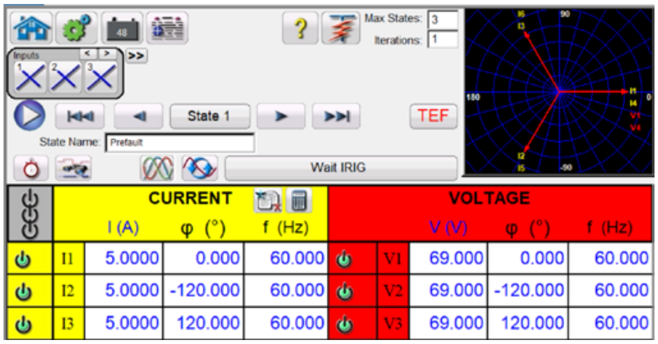
Figure 9 Traditional Test. Prefault State Test Set A



Max States: 3
Iterations: 1
State Name: Trip
Next Timeout (cy) 60
Wait Any (Continue)

	CURRENT				VOLTAGE		
	I (A)	φ (°)	f (Hz)		V (V)	φ (°)	f (Hz)
I1	10.000	-54.000	60.000	V1	35.371	-47.260	60.000
I2	10.000	126.000	60.000	V2	35.371	-72.740	60.000
I3	0.0000	0.000	60.000	V3	69.000	120.000	60.000

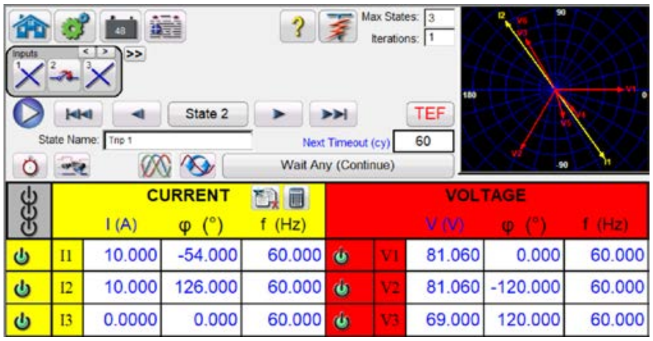
Figure 10 Traditional Test. Fault State Test Set A



Max States: 3
Iterations: 1
State Name: Prefault
Wait IRIG

	CURRENT				VOLTAGE		
	I (A)	φ (°)	f (Hz)		V (V)	φ (°)	f (Hz)
I1	5.0000	0.000	60.000	V1	69.000	0.000	60.000
I2	5.0000	-120.000	60.000	V2	69.000	-120.000	60.000
I3	5.0000	120.000	60.000	V3	69.000	120.000	60.000

Figure 11 Traditional Test. Pre-fault State Test Set B



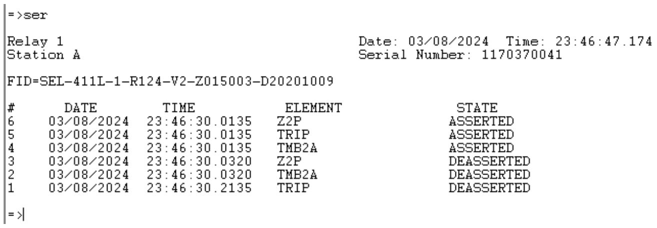
Max States: 3
Iterations: 1
State Name: Trip 1
Next Timeout (cy) 60
Wait Any (Continue)

	CURRENT				VOLTAGE		
	I (A)	φ (°)	f (Hz)		V (V)	φ (°)	f (Hz)
I1	10.000	-54.000	60.000	V1	81.060	0.000	60.000
I2	10.000	126.000	60.000	V2	81.060	-120.000	60.000
I3	0.0000	0.000	60.000	V3	69.000	120.000	60.000

Figure 12 Traditional Test-Fault State Test Set B

Similarly, Faults at any percentage of the Line values can be generated using the RTMS fault calculator.

Relay A at 10% of the Line fault.



```
=>ser

Relay 1                                       Date: 03/08/2024  Time: 23:46:47.174
Station A                                     Serial Number: 1170370041

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#       DATE          TIME             ELEMENT                STATE
6     03/08/2024  23:46:30.0135   Z2P                       ASSERTED
5     03/08/2024  23:46:30.0135   TRIP                      ASSERTED
4     03/08/2024  23:46:30.0135   TMB2A                     ASSERTED
3     03/08/2024  23:46:30.0320   Z2P                       DEASSERTED
2     03/08/2024  23:46:30.0320   TMB2A                     DEASSERTED
1     03/08/2024  23:46:30.2135   TRIP                      DEASSERTED

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```

Figure 13 Traditional Test. SER. Relay B. AB fault at 10%. POTT.

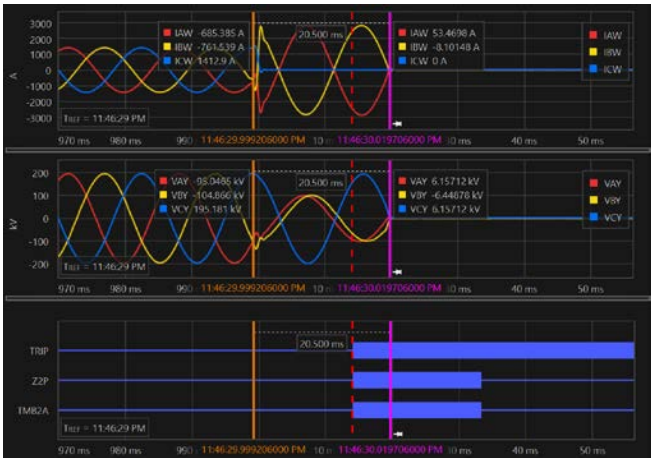
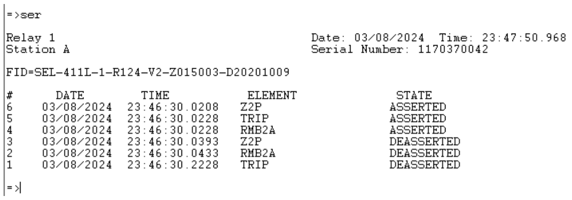


Figure 14. Traditional Test. AB fault. Relay A at 10%. POTT.

The relay A Trip logic is configured for the Z2P word bit. From the above events log we can see that Z2P is ASSERTED, the Trip is initiated, and a Permissive transfer trip is sent using TMB2A (i.e. Z2P Pickup) to the remote relay.
The fault cleared in 20.5 milliseconds.

Relay B at 90% of the Line fault.



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=>ser

Relay 1                                       Date: 03/08/2024  Time: 23:47:50.968
Station A                                     Serial Number: 1170370042

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#       DATE          TIME             ELEMENT                STATE
6     03/08/2024  23:46:30.0208   Z2P                       ASSERTED
5     03/08/2024  23:46:30.0228   TRIP                      ASSERTED
4     03/08/2024  23:46:30.0228   RMB2A                     ASSERTED
3     03/08/2024  23:46:30.0393   Z2P                       DEASSERTED
2     03/08/2024  23:46:30.0433   RMB2A                     DEASSERTED
1     03/08/2024  23:46:30.2228   TRIP                      DEASSERTED

=>
```

Figure 15 Traditional Test. SER. Relay B. AB fault at 90%. POTT

Relay B is configured to trip only when it receives a Permissive Trip and sees the fault in Zone 2. From the above events log we can see that Relay B sees the fault in Zone 2 as Z2P is Asserted, followed by initiating a Trip at the same time when it receives the permissive trip RMB2A.

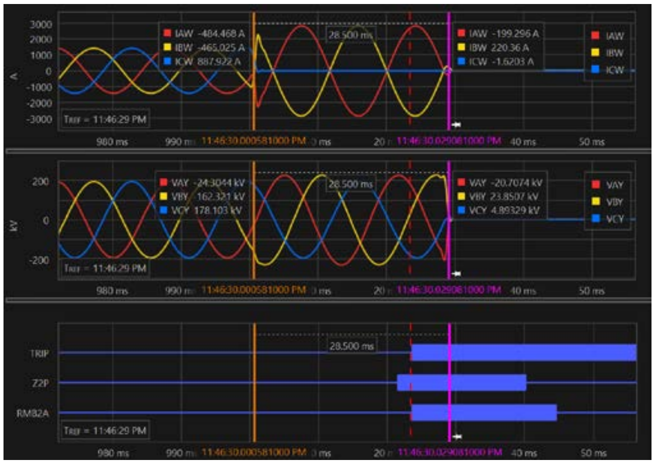
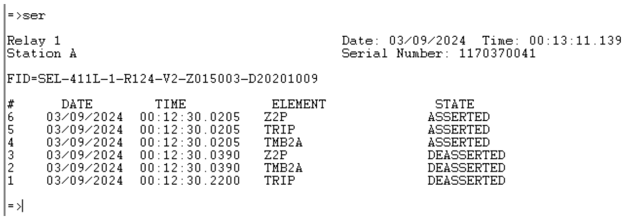


Figure 16. Traditional Test. AB fault. Relay B at 90%. POTT

The fault is cleared in 28.5 milliseconds.

Relay A at 90% of the Line fault.



```
=>ser

Relay 1                                       Date: 03/09/2024  Time: 00:13:11.139
Station A                                     Serial Number: 1170370041

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#       DATE          TIME             ELEMENT                STATE
6     03/09/2024  00:12:30.0205   Z2P                       ASSERTED
5     03/09/2024  00:12:30.0205   TRIP                      ASSERTED
4     03/09/2024  00:12:30.0205   TMB2A                     ASSERTED
3     03/09/2024  00:12:30.0390   Z2P                       DEASSERTED
2     03/09/2024  00:12:30.0390   TMB2A                     DEASSERTED
1     03/09/2024  00:12:30.2200   TRIP                      DEASSERTED

=>
```

Figure 17 Traditional Test. SER Relay A. AB fault at 90%. POTT

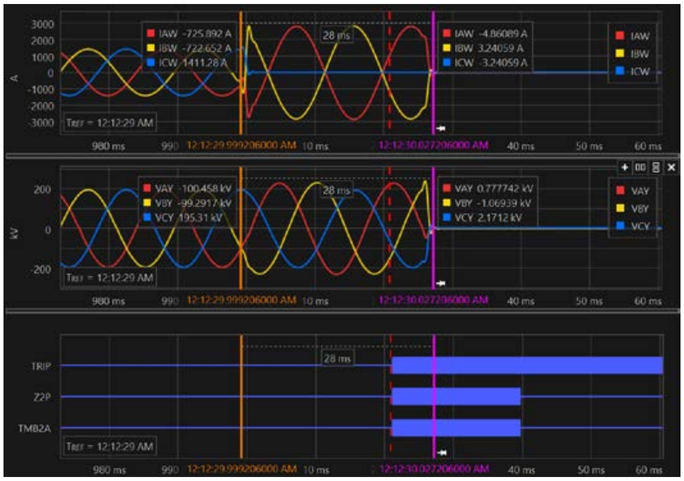
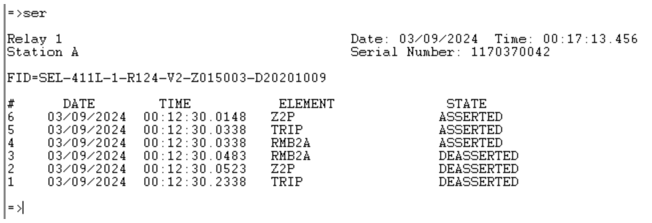


Figure 18 Traditional Test. AB fault. Relay A at 90%. POTT

The fault is cleared in 28 milliseconds.

Relay B at 10% of the Line fault.



```
=>ser

Relay 1                                          Date: 03/09/2024  Time: 00:17:13.456
Station A                                        Serial Number: 1170370042

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#       DATE         TIME           ELEMENT                STATE
6     03/09/2024  00:12:30.0148   Z2P                    ASSERTED
5     03/09/2024  00:12:30.0338   TRIP                   ASSERTED
4     03/09/2024  00:12:30.0338   RMB2A                  ASSERTED
3     03/09/2024  00:12:30.0483   RMB2A                  DEASSERTED
2     03/09/2024  00:12:30.0523   Z2P                    DEASSERTED
1     03/09/2024  00:12:30.2338   TRIP                   DEASSERTED

=>|
```

Figure 19 Traditional Test. SER. Relay B. AB fault at 10%. POTT.

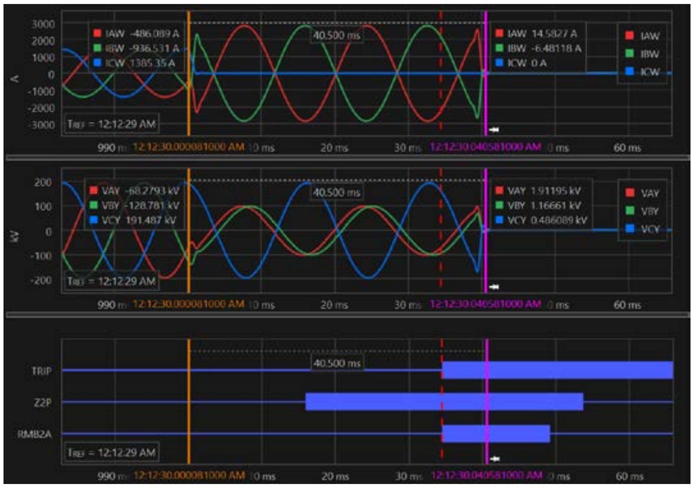


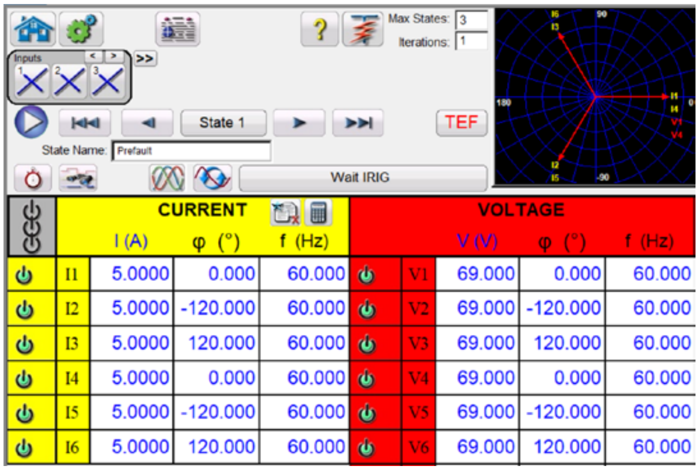
Figure 20 Traditional Test. AB Fault. Relay B at 10%. POTT

The fault is cleared in 40.5 milliseconds.

B. *Cloud-based POTT*

For the cloud-based testing, the injected values into the relays are the same as for the traditional tests shown above. The only difference is the testing method.

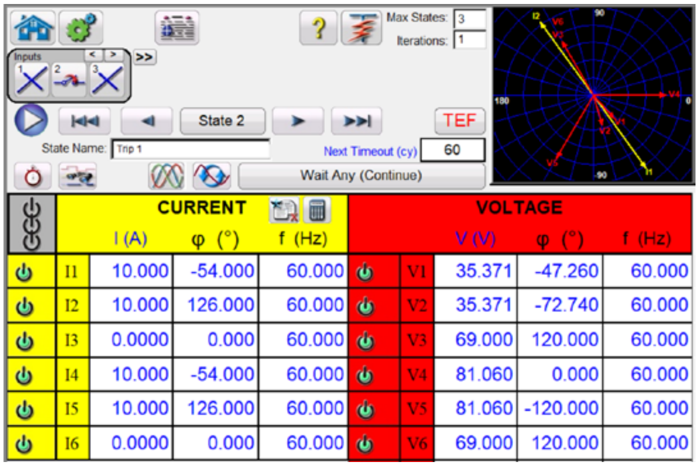
1) *Cloud-based Testing State Sequence Values*



Max States: 3
Iterations: 1
State 1
State Name: Prefault
Wait IRIG

		CURRENT					VOLTAGE		
		I (A)	φ (°)	f (Hz)			V (V)	φ (°)	f (Hz)
⏻	I1	5.0000	0.000	60.000	⏻	V1	69.000	0.000	60.000
⏻	I2	5.0000	-120.000	60.000	⏻	V2	69.000	-120.000	60.000
⏻	I3	5.0000	120.000	60.000	⏻	V3	69.000	120.000	60.000
⏻	I4	5.0000	0.000	60.000	⏻	V4	69.000	0.000	60.000
⏻	I5	5.0000	-120.000	60.000	⏻	V5	69.000	-120.000	60.000
⏻	I6	5.0000	120.000	60.000	⏻	V6	69.000	120.000	60.000

Figure 21 Cloud-Based Pre-fault State. All balanced values.



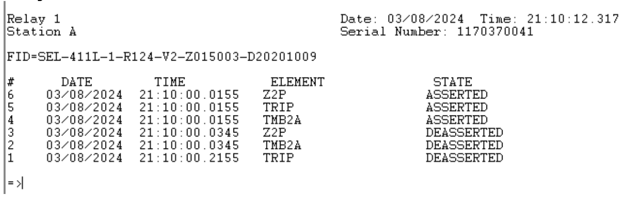
Max States: 3
Iterations: 1
State 2
State Name: Trip 1
Next Timeout (cy) 60
Wait Any (Continue)

		CURRENT					VOLTAGE		
		I (A)	φ (°)	f (Hz)			V (V)	φ (°)	f (Hz)
⏻	I1	10.000	-54.000	60.000	⏻	V1	35.371	-47.260	60.000
⏻	I2	10.000	126.000	60.000	⏻	V2	35.371	-72.740	60.000
⏻	I3	0.0000	0.000	60.000	⏻	V3	69.000	120.000	60.000
⏻	I4	10.000	-54.000	60.000	⏻	V4	81.060	0.000	60.000
⏻	I5	10.000	126.000	60.000	⏻	V5	81.060	-120.000	60.000
⏻	I6	0.0000	0.000	60.000	⏻	V6	69.000	120.000	60.000

Figure 22 Cloud-Based Fault State at 10% of the line of relay A.

Similarly, Faults at 90% of the Line values can be generated using the RTMS fault calculator.

Relay A 10% of the Line fault.



```
Relay 1                                          Date: 03/08/2024  Time: 21:10:12.317
Station A                                        Serial Number: 1170370041

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#       DATE         TIME           ELEMENT                STATE
6     03/08/2024  21:10:00.0155   Z2P                    ASSERTED
5     03/08/2024  21:10:00.0155   TRIP                   ASSERTED
4     03/08/2024  21:10:00.0155   TMB2A                  ASSERTED
3     03/08/2024  21:10:00.0345   Z2P                    DEASSERTED
2     03/08/2024  21:10:00.0345   TMB2A                  DEASSERTED
1     03/08/2024  21:10:00.2155   TRIP                   DEASSERTED

=>|
```

Figure 23 Cloud-Based Test. SER. Relay A AB fault at 10%. POTT

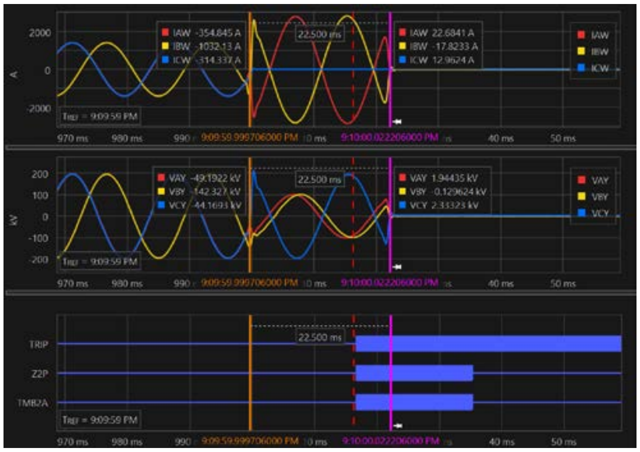
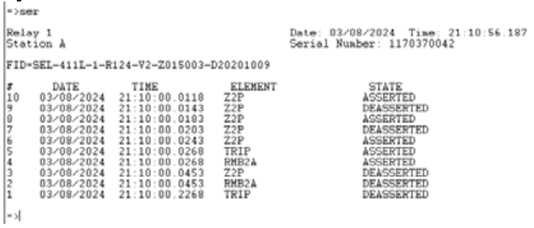


Figure 24 Cloud-Based Test. AB Fault Relay A at 10% POTT.

The fault is cleared in 22.5 milliseconds.

Relay B 90% of the Line fault.



```
=>ser

Relay 1                                          Date: 03/08/2024  Time: 21:10:56.187
Station A                                        Serial Number: 1170370042

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#       DATE         TIME           ELEMENT                STATE
10    03/08/2024  21:10:00.0118   Z2P                    ASSERTED
9     03/08/2024  21:10:00.0143   Z2P                    DEASSERTED
8     03/08/2024  21:10:00.0183   Z2P                    ASSERTED
7     03/08/2024  21:10:00.0203   Z2P                    DEASSERTED
6     03/08/2024  21:10:00.0243   Z2P                    ASSERTED
5     03/08/2024  21:10:00.0268   TRIP                   ASSERTED
4     03/08/2024  21:10:00.0268   RMB2A                  ASSERTED
3     03/08/2024  21:10:00.0453   Z2P                    DEASSERTED
2     03/08/2024  21:10:00.0453   RMB2A                  DEASSERTED
1     03/08/2024  21:10:00.2268   TRIP                   DEASSERTED

=>|
```

Figure 25 Cloud-Based Test. SER Relay B. AB Fault at 90%. POTT

Relay B sees the fault is in Zone 2 but waits for the permissive trip. Once it receives the permissive transfer trip at the same time trip is initiated.

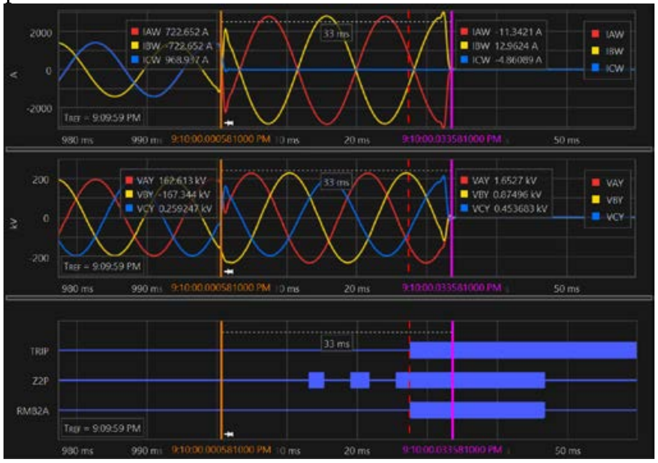
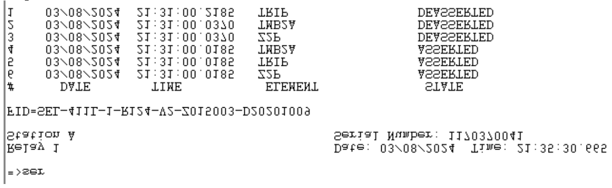


Figure 26 Cloud-Based Test. Relay B AB Fault at 90%. POTT.

The fault is cleared in 33 milliseconds.
Relay A 90% of the Line fault.



```
=>ser

Relay 1                                             Date: 03/08/2024  Time: 21:32:30.665
Station A                                           Serial Number: 1170370041

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#      DATE         TIME            ELEMENT               STATE
6   03/08/2024  21:31:00.0185   Z2P                   ASSERTED
5   03/08/2024  21:31:00.0185   TRIP                  ASSERTED
4   03/08/2024  21:31:00.0185   TMB2A                 ASSERTED
3   03/08/2024  21:31:00.0370   Z2P                   DEASSERTED
2   03/08/2024  21:31:00.0370   TMB2A                 DEASSERTED
1   03/08/2024  21:31:00.2185   TRIP                  DEASSERTED
```

Figure 27 Cloud-Based Test. SER, Relay A. AB Fault at 90%, POTT

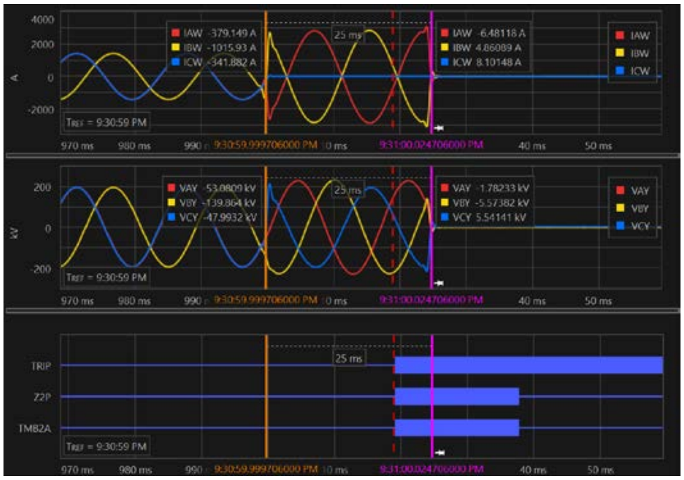
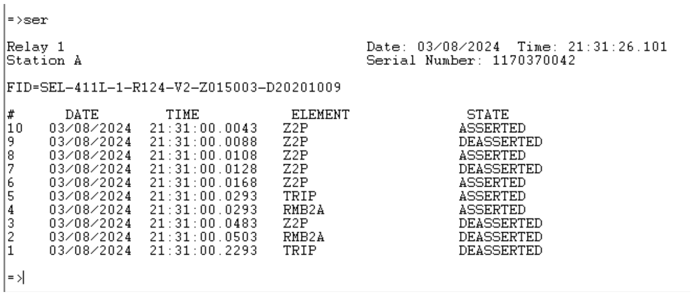


Figure 28 Cloud-Based Test. Relay A. AB Fault at 90%. POTT

The fault is cleared in 25 milliseconds.
Relay B 10% of the Line fault.



```
=>ser

Relay 1                                             Date: 03/08/2024  Time: 21:31:26.101
Station A                                           Serial Number: 1170370042

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#      DATE         TIME            ELEMENT               STATE
10  03/08/2024  21:31:00.0043   Z2P                   ASSERTED
9   03/08/2024  21:31:00.0088   Z2P                   DEASSERTED
8   03/08/2024  21:31:00.0108   Z2P                   ASSERTED
7   03/08/2024  21:31:00.0128   Z2P                   DEASSERTED
6   03/08/2024  21:31:00.0168   Z2P                   ASSERTED
5   03/08/2024  21:31:00.0293   TRIP                  ASSERTED
4   03/08/2024  21:31:00.0293   RMB2A                 ASSERTED
3   03/08/2024  21:31:00.0483   Z2P                   DEASSERTED
2   03/08/2024  21:31:00.0503   RMB2A                 DEASSERTED
1   03/08/2024  21:31:00.2293   TRIP                  DEASSERTED

=>
```

Figure 29 Cloud-Based Test. SER Relay B. AB Fault at 10%. POTT.

Relay B sees the fault is in Zone 2 but is waiting for the permissive trip. Once it receives the permissive transfer trip, it initiates the trip at the same time.

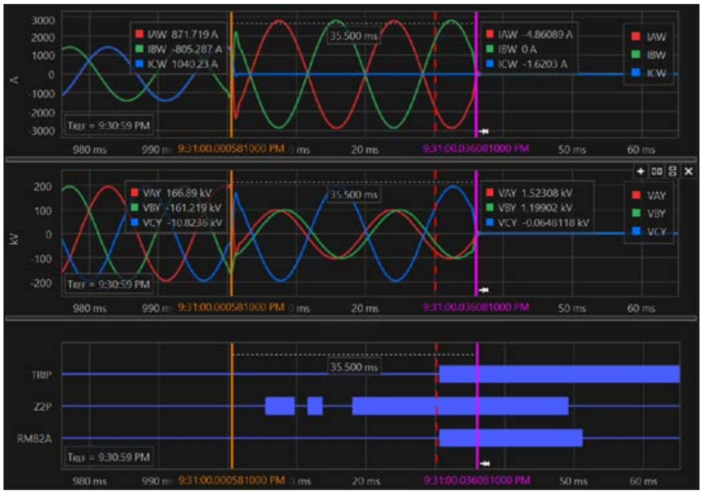


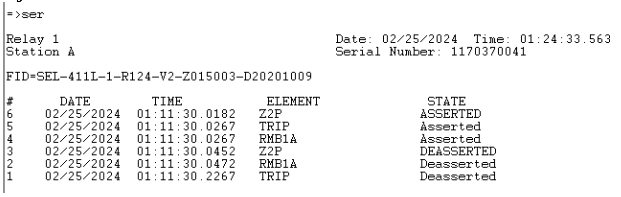
Figure 30 Cloud-Based Test. Relay B at 10%. POTT

The fault is cleared in 35.5 milliseconds.

Traditional PUTT:

In this PUTT scheme, the Trip logic is configured to “Z1P OR (Z2P AND Transfer trip)”. As you see the fault is at 90% of the line in Zone 2, for the trip to initiate the relay is waiting to receive the permissive transfer trip RMB1A from Relay B. As soon as Relay A receives RMB1A, a trip is initiated at the same time.

Relay A 90% of the Line fault.



```
=>ser

Relay 1                                             Date: 02/25/2024  Time: 01:24:33.563
Station A                                           Serial Number: 1170370041

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#      DATE         TIME            ELEMENT               STATE
6   02/25/2024  01:11:30.0182   Z2P                   ASSERTED
5   02/25/2024  01:11:30.0267   TRIP                  Asserted
4   02/25/2024  01:11:30.0267   RMB1A                 Asserted
3   02/25/2024  01:11:30.0452   Z2P                   DEASSERTED
2   02/25/2024  01:11:30.0472   RMB1A                 Deasserted
1   02/25/2024  01:11:30.2267   TRIP                  Deasserted
```

Figure 31 Traditional Test. Relay A. AB fault at 90 %. PUTT.

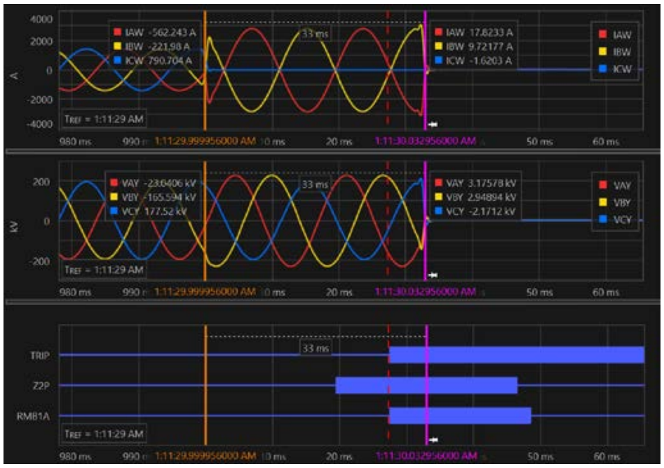
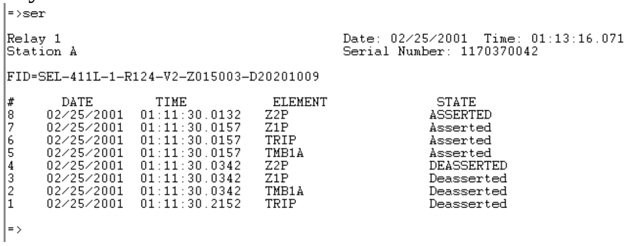


Figure 32 Traditional Test. Relay A. AB Fault at 90%. PUTT.

The fault is cleared in 33 milliseconds.

Relay B 10% of the Line fault.



```
=>ser

Relay 1                                    Date: 02/25/2001  Time: 01:13:16.071
Station A                                  Serial Number: 1170370042

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#      DATE        TIME            ELEMENT                 STATE
8    02/25/2001  01:11:30.0132   Z2P                     ASSERTED
7    02/25/2001  01:11:30.0157   Z1P                     Asserted
6    02/25/2001  01:11:30.0157   TRIP                    Asserted
5    02/25/2001  01:11:30.0157   TMB1A                   Asserted
4    02/25/2001  01:11:30.0342   Z2P                     DEASSERTED
3    02/25/2001  01:11:30.0342   Z1P                     Deasserted
2    02/25/2001  01:11:30.0342   TMB1A                   Deasserted
1    02/25/2001  01:11:30.2152   TRIP                    Deasserted

=>
```

Figure 33 Traditional Test. SER Relay B. AB fault at 10%. PUTT.

As the fault is at 10% of the line, it is a Zone 1 fault. Relay B initiated a Trip without waiting for a Permissive Trip and sent a Transfer Trip using TMB1A to Relay A.

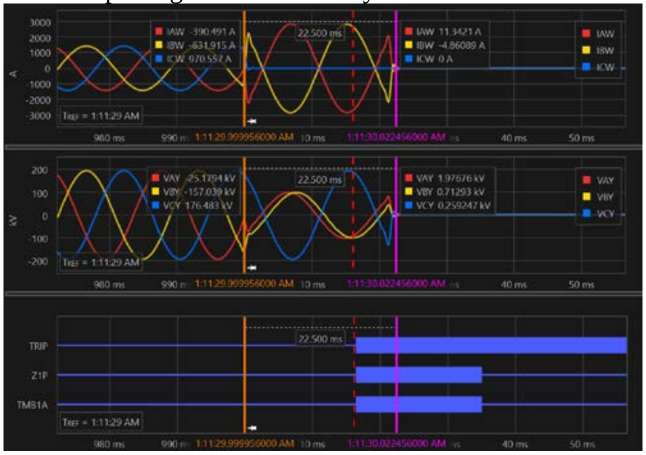


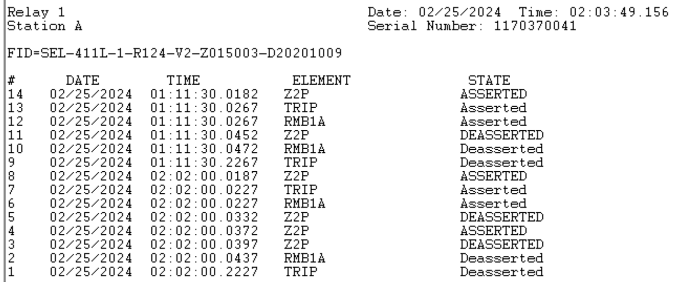
Figure 34 Traditional Test. Relay B. AB Fault at 10%. PUTT.

The fault is cleared in 22.5 milliseconds.

Cloud-Based PUTT**:**

Like the above case, this test is performed using a cloud-based end-to-end testing method. The fault is in Zone 2, the Z2P bit is Asserted and is waiting to receive the permissive transfer bit RMB1A. Once it receives the RMB1A, the trip is initiated at the same time.

Relay A 90% of the Line fault.



```
Relay 1                                    Date: 02/25/2024  Time: 02:03:49.156
Station A                                  Serial Number: 1170370041

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#      DATE        TIME            ELEMENT                 STATE
14   02/25/2024  01:11:30.0182   Z2P                     ASSERTED
13   02/25/2024  01:11:30.0267   TRIP                    Asserted
12   02/25/2024  01:11:30.0267   RMB1A                   Asserted
11   02/25/2024  01:11:30.0452   Z2P                     DEASSERTED
10   02/25/2024  01:11:30.0472   RMB1A                   Deasserted
9    02/25/2024  01:11:30.2267   TRIP                    Deasserted
8    02/25/2024  02:02:00.0187   Z2P                     ASSERTED
7    02/25/2024  02:02:00.0227   TRIP                    Asserted
6    02/25/2024  02:02:00.0227   RMB1A                   Asserted
5    02/25/2024  02:02:00.0332   Z2P                     DEASSERTED
4    02/25/2024  02:02:00.0372   Z2P                     ASSERTED
3    02/25/2024  02:02:00.0397   Z2P                     DEASSERTED
2    02/25/2024  02:02:00.0437   RMB1A                   Deasserted
1    02/25/2024  02:02:00.2227   TRIP                    Deasserted
```

Figure 35. Cloud-Based Test. Relay A. AB Fault at 90%. PUTT

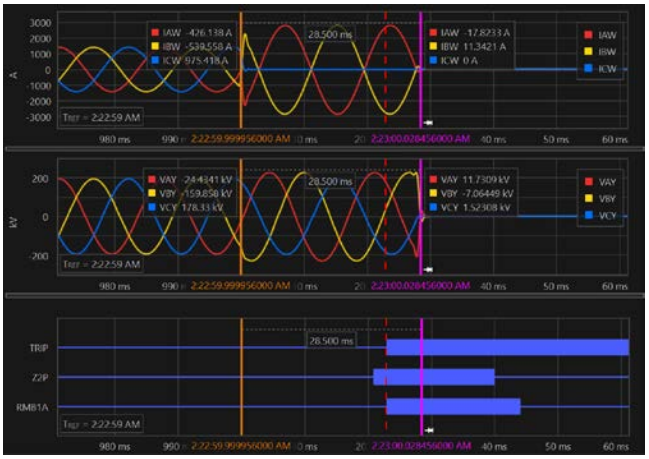
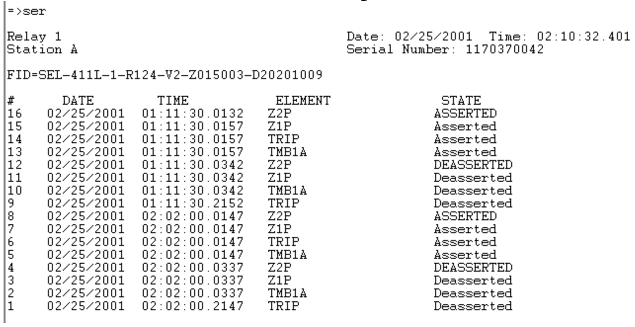


Figure 36 Cloud-Based Test. Relay A. AB Fault at 90%. PUTT.

The fault is cleared in 28.5 milliseconds**.**

Relay B 10% of line Fault.

Like the above cases, the fault is in Zone 1, and the Z1P bit is asserted. At the same time, the trip is initiated.



```
=>ser

Relay 1                                    Date: 02/25/2001  Time: 02:10:32.401
Station A                                  Serial Number: 1170370042

FID=SEL-411L-1-R124-V2-Z015003-D20201009

#      DATE        TIME            ELEMENT                 STATE
16   02/25/2001  01:11:30.0132   Z2P                     ASSERTED
15   02/25/2001  01:11:30.0157   Z1P                     Asserted
14   02/25/2001  01:11:30.0157   TRIP                    Asserted
13   02/25/2001  01:11:30.0157   TMB1A                   Asserted
12   02/25/2001  01:11:30.0342   Z2P                     DEASSERTED
11   02/25/2001  01:11:30.0342   Z1P                     Deasserted
10   02/25/2001  01:11:30.0342   TMB1A                   Deasserted
9    02/25/2001  01:11:30.2152   TRIP                    Deasserted
8    02/25/2001  02:02:00.0147   Z2P                     ASSERTED
7    02/25/2001  02:02:00.0147   Z1P                     Asserted
6    02/25/2001  02:02:00.0147   TRIP                    Asserted
5    02/25/2001  02:02:00.0147   TMB1A                   Asserted
4    02/25/2001  02:02:00.0337   Z2P                     DEASSERTED
3    02/25/2001  02:02:00.0337   Z1P                     Deasserted
2    02/25/2001  02:02:00.0337   TMB1A                   Deasserted
1    02/25/2001  02:02:00.2147   TRIP                    Deasserted
```

Figure 37 Cloud-Based Test. Relay B. AB Fault at 10%. PUTT.

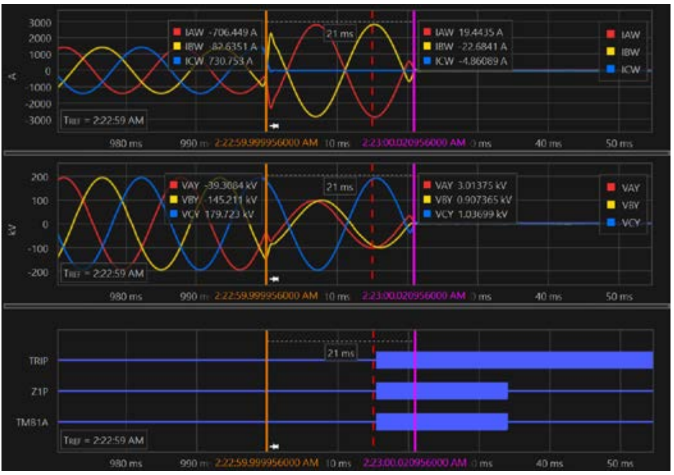


Figure 38 Cloud-Based Test. Relay B. AB Fault at 10%. PUTT.

The fault is cleared in 21 milliseconds.

Table 2 Trip time comparison

Trip Time Assessment				
	Traditional method	Cloud-based end-to-end		
Time	**POTT**	**PUTT**	**POTT**	**PUTT**
Average Time (Cycles)	1.71	1.63	1.57	1.47
Max Time (Cycles)	2.43	2.07	2.05	1.92
Minimum Time (Cycles)	1.23	1.35	1.35	1.26

As a somewhat surprising result, we found that during the cloud-based testing, the trips happened on average between 2 and 2.75 milliseconds faster (I.e. 0.12 – 0.16 Cycles).

VIII. CONCLUSION

Cloud-based end-to-end testing can enhance the user testing experience. It provides similar results to traditional methods, but it streamlines the testing process, cutting the testing time and test requirements.

With growing technology trends, it's all about making a better way to test power systems. It shows us a future where testing is more straightforward, needs fewer resources, and can be done from anywhere.

Our analysis reveals that cloud-based testing yields similar results to traditional methods. By using cloud technology, we can do these tests more easily with better visualization, and with fewer mistakes compared to the old ways of testing. This means we can get the same good results but faster and without needing as many skilled resources as possible.

In conclusion, the cloud-based end-to-end testing methodology presented in this paper not only aligns with the current digital transformation trends in power systems but also sets a new standard for the testing and validation of protection schemes. As we continue to explore the capabilities of cloud computing, it is evident that its integration into power system protection offers a promising path toward achieving higher efficiency, reliability, and adaptability in our quest to safeguard our electrical grids. This study serves as a foundation for future research and development in the field, encouraging further exploration into the possibilities that cloud technology holds for enhancing power system protection.

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