Methodologies and Processes to Enhance the Accuracy, Technical Quality, and Efficacy of Protective Relay Testing using COMTRADE Files

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1.   SUMMARY

With the increasing complexity of protection settings and schemes, developing new approaches for thorough testing of protective devices prior to or at the commissioning phase has become imperative. Given that numerical relays have become very reliable, the tolerance and accuracy of protection elements does not need to be verified at the commissioning stage, but rather the focus should be on verifying the relay settings in a situation as close as possible to real-world conditions. Some utilities use Microsoft Excel spreadsheets to compute current/voltage phasor values associated with various fault scenarios injected to a relay for testing purposes at the commissioning stage. However, since the entire topology of the system is not taken into consideration in the current procedure, the effect of mutual coupling, decaying DC, and infeed/outfeed contribution on the network element, along with other parameters related to the system topology, are not fully reflected in the computed phasors. In addition, the test points are computed based on the issued setting file in the existing processes. Therefore, any error in setting parameters can affect the accuracy of the test points. Such test points can be used to verify the protection logic but do not confirm the accuracy of the setting values. Since procedures are executed manually, the process is prone to human error, and standardization may be challenging.

In this paper, we demonstrate how some of the shortcomings of existing testing procedures can be tackled. We propose new methods and tools that would improve the accuracy and efficacy of relay testing using Common format for Transient Data Exchange (COMTRADE) files, generated by using various short-circuit calculation programs. COMTRADE files can be played in numerical protective devices using the existing testing equipment to simulate various fault scenarios for lines, transformers, and busbars. Since a short-circuit calculation program accounts for the impact of the entire system topology, the generated COMTRADE files will better replicate the actual fault current and voltage signals, thereby producing more reliable test results. COMTRADE files are generated independent from setting parameters, thus the new procedure can detect issues caused during setting parameter calculation. Moreover, the generation of COMTRADE files has been automated using scripts to alleviate the possibility of human error and help standardize the process.

We indicate how each protection scheme can be tested under a condition very similar to the real-world application while also reducing the cost and complexity of the testing procedure. Various system conditions, including N-1 contingencies and system reconfiguration during the fault, have been carefully considered to create a testing platform as close to real-world conditions as possible. In addition to substantially increasing the quality and accuracy of the testing, we also present methods and tools used to automate the relay testing and reporting.

The methods proposed in this paper have been utilized to create a tool that is currently utilized by a power transmission utility at the pilot stage. The efficacy of the developed tools has been verified via lab testing and analysis.

Through case studies and simulations, it is indicated that the developed tool can be used to avoid various protection setting errors before or at the commissioning stage that would otherwise have not been detected. In addition to reducing potential human error, the proposed method for testing can facilitate the execution of the testing procedure, thereby reducing the cost and time associated with each commissioning project. The developed tools can also create COMTRADE files for studies, analysis, and troubleshooting prior to issuing the final setting file.

KEYWORDS

Automation, Relay Testing, COMTRADE, Transmission Protection, Modelling and Simulation, Field Test, Commissioning, Process Enhancement, Labour Cost, Relay Setting File

2.   EXISTING PROCESS FOR RELAY TESTING AND COMMISSIONING

The existing process for relay testing and commissioning is normally based on Microsoft Excel© workbooks as both a guideline for test process execution and a record of the test results. The relay test equipment manufacturers also may provide procedures for calculation of the test points. As shown in Figure 1, such workbooks take in system parameters and relay settings, calculate voltage and current phasor values (test points) for each fault scenario to be utilized for the relay testing. These workbooks also contain tables where the field engineer can use to keep a record of each test.
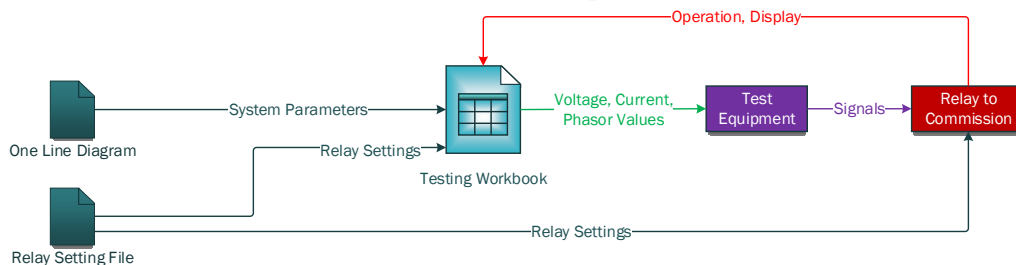

Figure 1. Existing process for relay testing and commissioning

The test points computed by the workbook are applied to the relay by the engineer as per the guideline. From a technical perspective, the existing testing process does not factor in the following items:
- The effect of mutual coupling with neighboring lines on the study line
- The decaying DC component (offset DC) of the fault current
- The impact of system topology and system configuration
- The effect of outfeed or infeed contribution in multi-terminal lines
- Inability to create a wide range of tests due to limited test scenarios

Besides the technical viewpoint, the existing process can be improved from the process perspective:
- Human errors such as entering the incorrect current/voltage phasor values into the testing device
- Being dependent on the decisions made by individual operators, thereby making standardization challenging

This paper aims to tackle the shortcomings mentioned above by proposing new methodologies and processes to enhance the accuracy, technical quality, and efficacy of protective relay testing using COMTRADE files.

3.   PROPOSED COMTRADE-BASED METHOD FOR RELAY TESTING

With the proposed process and tools, the fault current/voltage phasor values are more like the real-world system's values than the formula-based calculations in the conventional testing process. Additionally, the fault simulation process would be prone to less human error given that COMTRADE files are generated using an automated procedure. Figure 2 below shows the high-level process of the COMTRADE-based relay testing procedure for a transmission line as an example. This paper also proposes a process for transformer and bus protection testing.
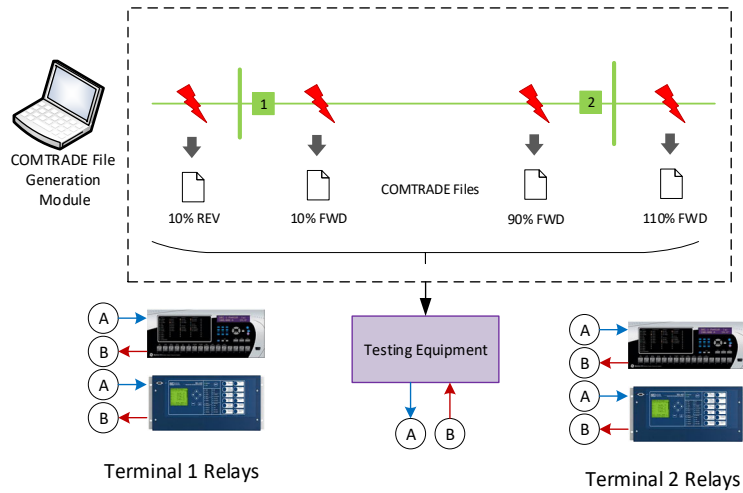
Figure 2. High-level process of the COMTRADE-based relay testing for a transmission line

As shown in Figure 2, COMTRADE files are generated using the developed tool for various fault locations and played back to the relays. One of the major components of the proposed process for COMTRADE file generation is automated scripts known as macros. These automated scrips would typically interface with a power system network model executed by a short-circuit calculation software for COMTRADE file generation. It is worth noting that the fault current and voltage phasor values are computed by the short-circuit calculation software and then turned into COMTRADE format synthetically using the developed scripts considering the impact of decaying DC.
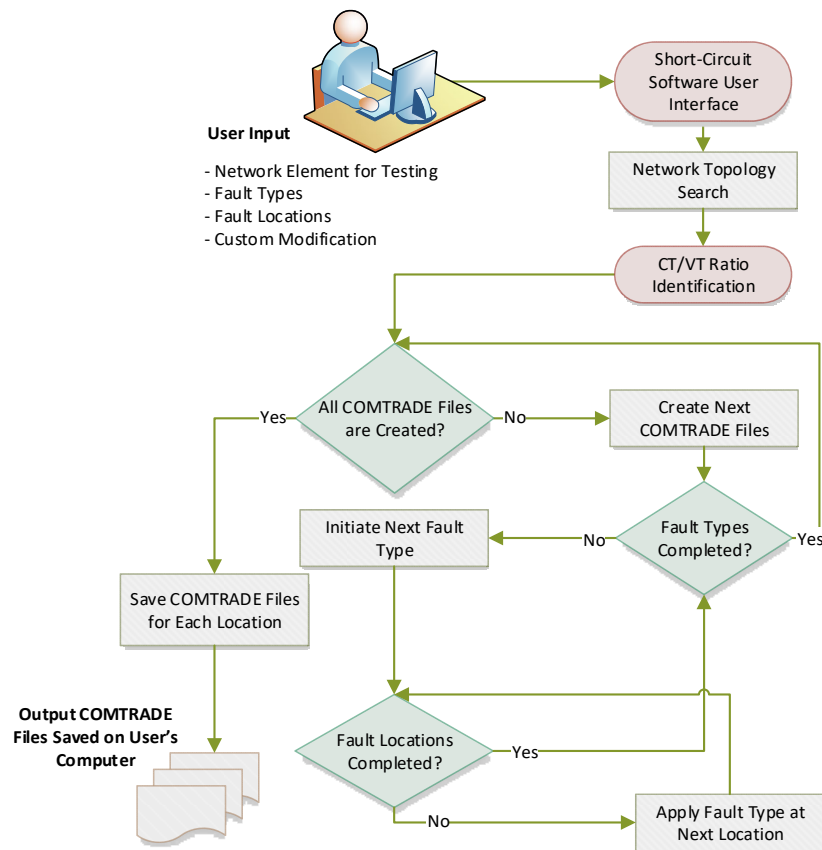

Figure 3. COMTRADE file generation procedure using automated scrips, also known as macros

As shown in Figure 2, the user interfaces with a short-circuit calculation software for COMTRADE file generation through various self-explanatory steps in the figure. It should be noted that the process shown in the figure is executed automatically and only requires capturing the user's input via the graphical user interface (GUI).

Figure 4 shows a typical network configuration in the short-circuit calculation software and various fault locations for COMTRADE file generation.
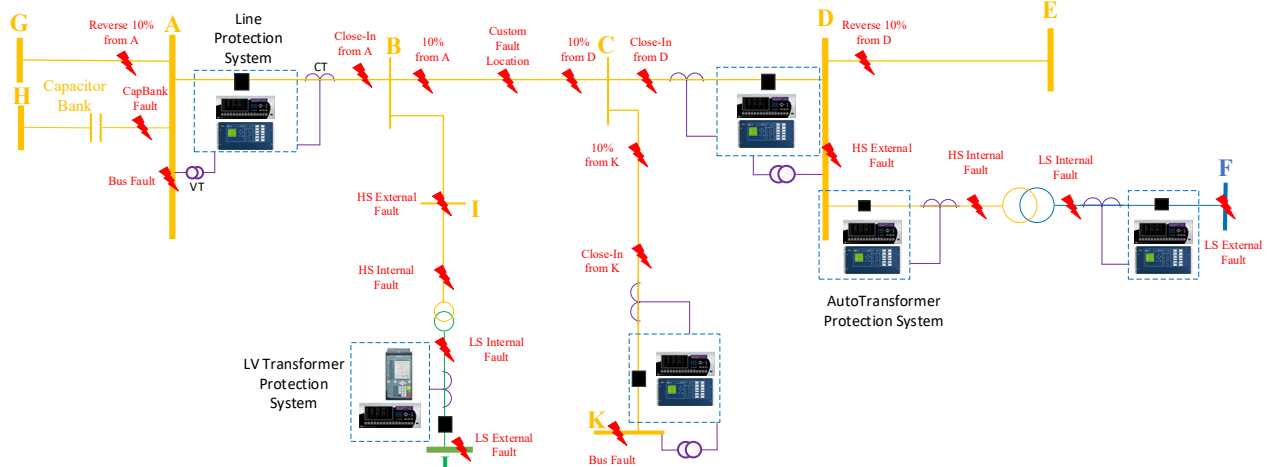

Figure 4. A typical network configuration for generation of various COMTRADE files

The COMTRADE files generated based on the scenarios depicted in Figure 4 are used to test the following network elements: line, auto-transformer, low-voltage (LV) transformer, and busbar. To test each element under the same scenario that the element is exposed to in real life, the system configurations are replicated in the short circuit program, and then COMTRADE files are generated. Examples of two cases are represented in Figure 5.
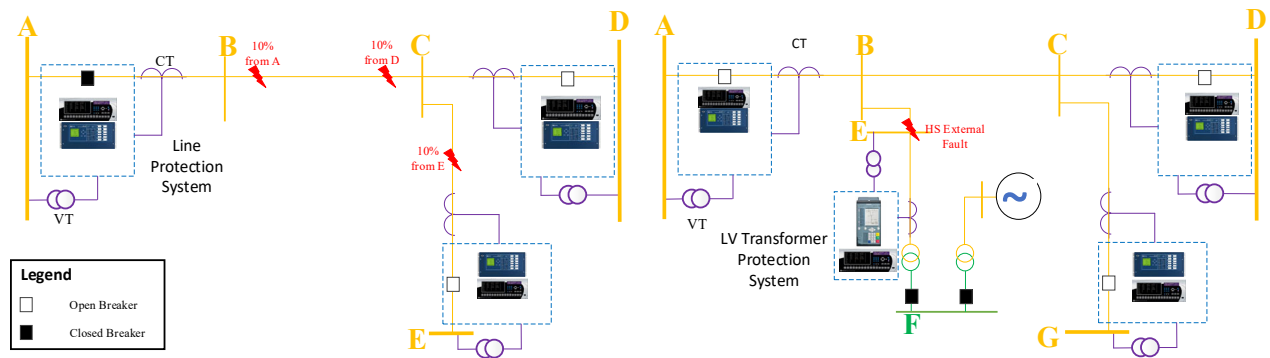
(a): Comtrade file generation under sequential line tripping   (b): Comtrade file generation for line backup relay testing

Figure 5. COMTRADE file generation under actual system configurations

As shown in Figure 5 (a), the circuit breaker (CB) at Terminal A is opened automatically by the tool, a fault is applied at 10% from Terminal A, and COMTRADE files are generated for relay testing at Terminals D and E. A similar procedure is applied where CBs at terminals D and E are opened by the tool, and COMTRADE files are generated for the other two terminals. In addition, in Figure 5 (b), faults are line CBs are opened, and the fault is applied at HS of the transformer to test the line backup protection relay under the same condition as it operates in the field.

4. SIMULATION AND ANALYSIS

As discussed earlier in the paper, COMTRADE files are created in a software environment and played back to the relay in the field for relay testing. Figure 6 shows COMTRADE files created under different test scenarios using an actual power network model.

(a): COMTRADE waveforms for line fault

(b): COMTRADE waveforms for line fault with sequential tripping

(c): COMTRADE waveforms for load encroachment test

(d): COMTRADE waveforms for line fault with DC offset

(e): COMTRADE waveforms for transformer external fault

(f): COMTRADE waveforms for transformer internal fault

(g): COMTRADE waveforms including 2nd harmonics

(h): COMTRADE waveforms for line backup testing

(i): COMTRADE waveforms for RGF element testing (external fault)

(j): COMTRADE waveforms for RGF element test (internal fault)

(k): COMTRADE waveforms for busbar testing (external fault)

(l): COMTRADE waveforms for busbar testing (internal fault)

Legend

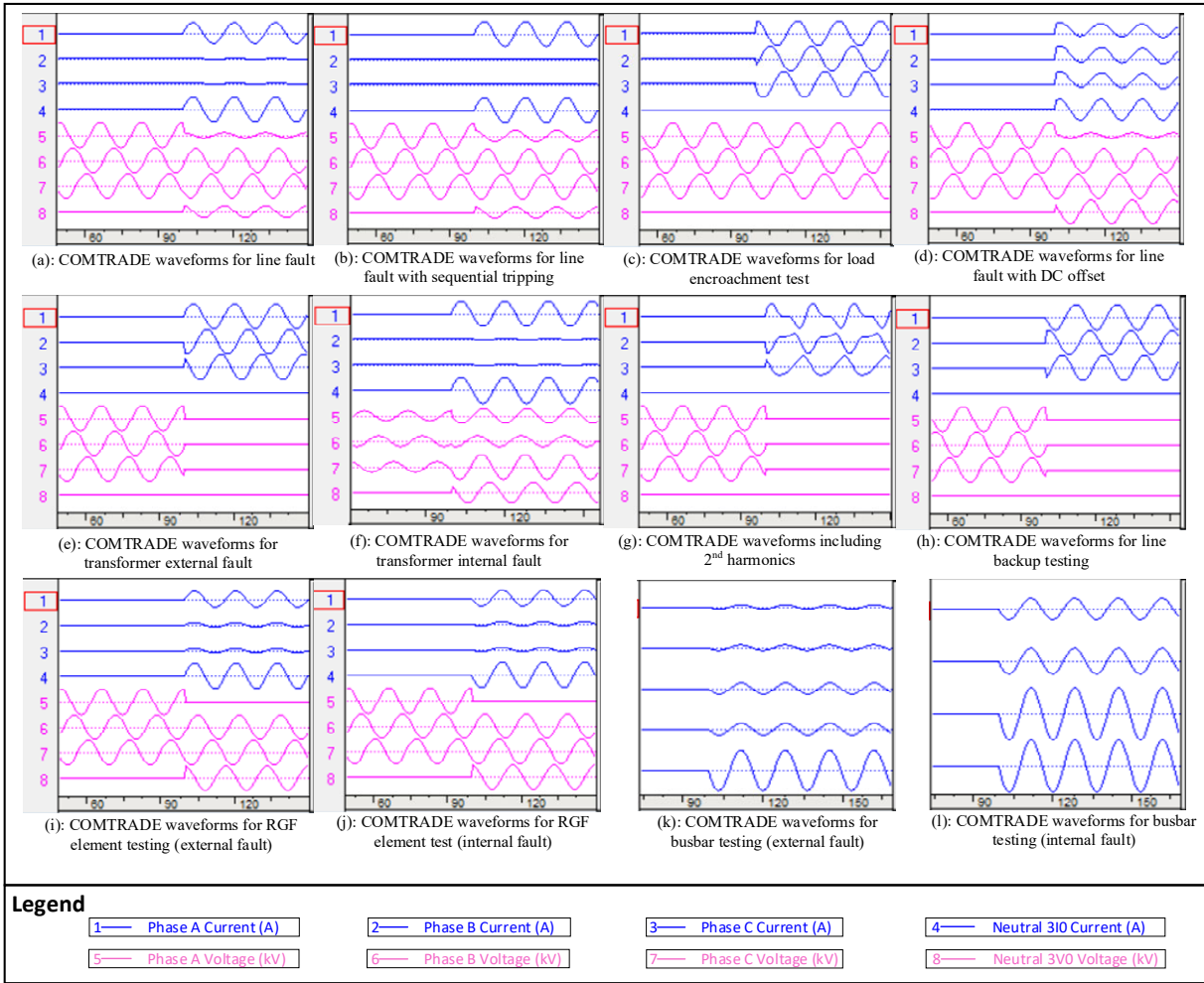|			
1 —— Phase A Current (A)	2 —— Phase B Current (A)	3 —— Phase C Current (A)	4 —— Neutral 3I0 Current (A)
5 —— Phase A Voltage (kV)	6 —— Phase B Voltage (kV)	7 —— Phase C Voltage (kV)	8 —— Neutral 3V0 Voltage (kV)

Figure 6. COMTRADE files generated using network simulation software for different test cases

As shown in Figure 6, the COMTRADE waveforms differ in shape and values depending on their created scenario. Such scenarios are carefully designed to ensure that the COMTRADE files are as close to the real-life voltage and current signals.

5. RELAY TESTING FIELD DATA

The COMTRADE file playback has been introduced to various substations and used to commission line distance protection, bus differential protection, transformer differential protection.

To facilitate the field testing, the protection and control (P&C) technical service provides commissioning workbooks and COMTRADE files to the field for each relay commissioning. The COMTRADE files are played back to the relay using test equipment, and the relay behavior for each fault condition is recorded in the workbook, as shown in Figure 7. Element pickup, LED indication, and trip times are manually recorded in the workbook to indicate a "Pass" or "Fail" for the test cases as shown in Figure 7. The recorded data in the test workbook for various pilot projects have been analyzed to evaluate the efficacy of the proposed COMTRADE playback approach from technical and economic viewpoints. As discussed below, the test results collected from the field show significant improvement in both the reliability and labor cost.

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5.6.1	PHASE DISTANCE Elements In-Zone/Out-Zone without permissive and transfer trip (Local Test)									
PREFAULT	Simulate breaker closed by applying DC to breaker pallets input									
PREFAULT	Open 77MR/AR&MT/AT and 69MR/AR&MT/AT input at local terminal									
INITIAL INPUT CONDITION	Prot In Test	H51/a	H52/a	DS/b	H51 BF	H52 BF	RESERVED	RESERVED	RESERVED	RESERVED
	A94-77S	A77MR/Terminal 2	RESERVED	A69MR/Terminal 2	RESERVED	A77AR/Terminal 2	RESERVED	A69AR/Terminal 2	RESERVED	ZTT
Test Case	Play back COMTRADE file at local terminal		Comtrade File Name		77&69 I/O BS	Expected local operation	Trip Time	PASS/FAIL		
	Comtrade File Name Convention: XX10[Where the fault is applied]_FOR[Forward or Reverse]_10[10% of the line impedance]_XD12[Where the measurement is taken]_LL[Fault type] LL: Line to Line Fault									
1	10% forward fault from Terminal 1		XX10_FOR_10_XX10_LL		Open	Z1P				
2	Bus fault from Terminal 1		XX10_BUS_XX10_LL		Open	No trip				
3	10% forward fault from Terminal 2		XD12_FOR_10_XX10_LL		Open	Z2P Timed				
4	Bus fault from Terminal 2		XD12_BUS_XX10_LL		Open	No trip				

Figure 7. Workbook for capturing the operation of protective relays tested at commissioning stage using COMTRADE playback

5.1 Reliability Improvement Analysis Using Field Data

The field data collected/analyzed during relay testing and commissioning indicate that:

- The field personnel no longer need to manually inject current and voltage setpoints to the relay. Instead, automatically generated COMTRADE files containing the current and voltage waveforms are utilized for each test case. This would help significantly reduce the human effort during the relay commissioning.
- The relay behavior is tested under conditions very close to the real-life condition as opposed to using calculated test points. As such, inadvertent trips due to setting errors can be captured during commissioning.
- The conventional test method can be used to verify the relay behavior locally. However, the new test method applies different COMTRADE files for the same fault at multiple locations to achieve more comprehensive testing, thereby capturing settings issues that could have otherwise gone undetected using the conventional testing procedure.

To indicate the efficacy of the proposed method, two real-life examples are presented below. The COMTRADE generation module was used to verify relay setting issues that were not captured using the conventional process, thereby causing a field misoperation.

5.1.1 Real-Life Example One

A misoperation happened at a substation where a transmission line is erroneously tripped out for a fault on the adjacent transmission line (Substation 2 in Figure 8). The misoperation stemmed from the uncoordinated overcurrent supervision at Substation 1 in Figure 8.
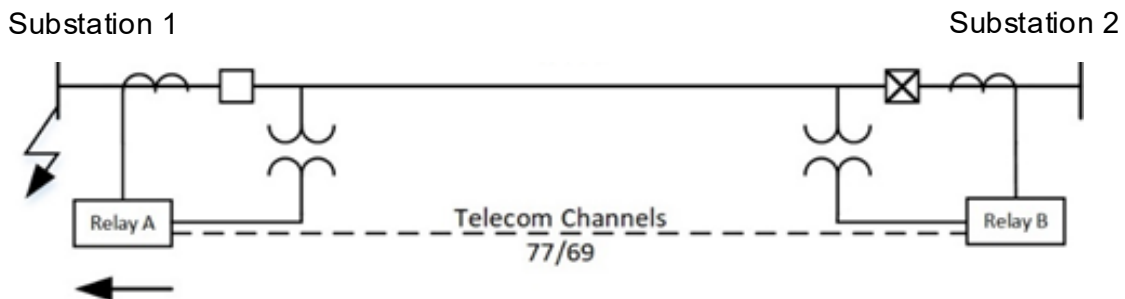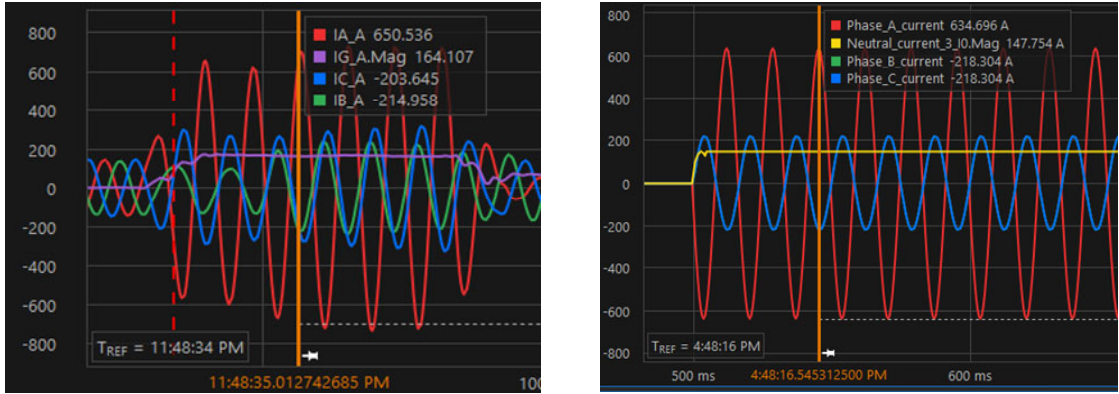

Figure 8. Field misoperation of a transmission line

| (a): Actual event record data from the SEL-421 relay in a substation | (b): Generated COMTRADE waveforms using the proposed method and the network model |

Figure 9. Actual vs generated current COMTRADE for the misoperation event

The line scheme is shown in Figure 8, and the actual and simulated COMTRADE current waveforms are shown in Figure 9 (for Substation 1). As per the line protection guideline, the 50N overcurrent supervision for a directional comparison blocking (DCB) scheme was set to 0.1pu, which turns into 320 A for Substation 1. However, the fault current generated only 164.1 A (as shown in Figure 9 (a)) when a single phase to ground fault occurred on a bus at Substation 1. Because the fault current was below the 50N pickup setting, the blocking signal was not triggered, and the bus fault caused an over-tripping at Substation 2.

The scenario mentioned above was simulated on the relevant power network model using the short-circuit calculation software, where a fault is applied on the bus, and COMTRADE files were generated using the proposed tool as represented in Figure 9 (b). Comparing the simulated current values and the actual ones shown in Figure 9 (a) and (b), one can see that the simulated fault currents are fairly close to the actual values indicating that both the simulated network model and the proposed tool for COMTRADE generation are accurate. When playing back the generated COMTRADE file to the relay with the incorrect settings, the same behavior as the real-life event was captured. This would indicate that the issue could have been prevented using the proposed COMTRADE-based testing.

5.1.2   Real-Life Example Two

In a substation, the transformer protection system misoperated due to incorrect winding two voltage settings (115.5 kV instead of 44kV). Figure 10 shows the fault location with respect to the transformer protection zone.
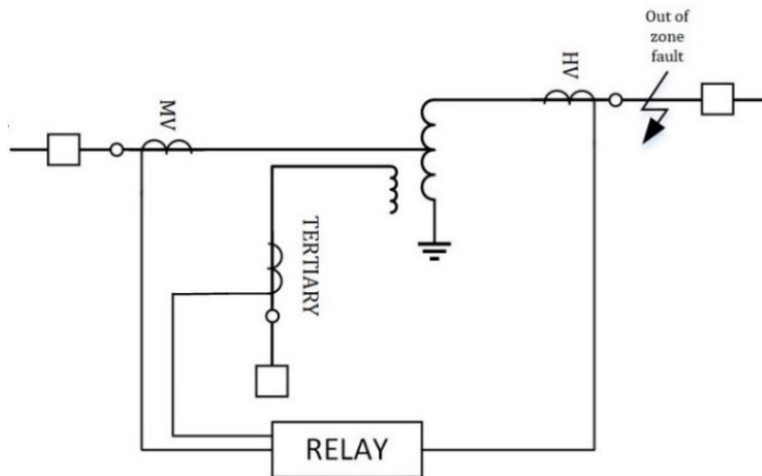

Figure 10. Field misoperation of a distribution transformer

As shown in Figure 10, a single-phase to ground fault occurred on the transformer medium voltage bus. It was an out-of-zone fault, and thus, should not have triggered the differential protection. However, due to the incorrect winding two voltage setting, the fault currents from the high voltage side and the medium voltage side did not cancel each other. Therefore, the differential protection system operated and tripped the transformer.

The fault on the bus was simulated using the proposed model, and the relevant COMTRADE files were captured. When the COMTRADE files are played back to the faulty setting file, the same behavior as the real-life event was captured. The advantage of the proposed testing method is that it evaluates the settings independent from the relay setting file, thus setting issues do not affect the accuracy of the test cases. This would indicate that the issue could have been prevented using the proposed COMTRADE-based testing.

5.2   Labour Cost Improvement Analysis

The proposed method's commissioning labor cost has been compared with the cost associated with the conventional method. The labour cost reduction for the proposed COMTRADE-based testing in comparison with the conventional testing method can be estimated up to 54% for standard protection system designs and 55% for nonstandard designs.

6.   CONCLUSION

This paper demonstrates how some of the shortcomings of conventional relay testing and commissioning procedures utilized by transmission power utilities can be tackled. We propose new methods and tools that would improve the accuracy and efficacy of relay testing and commissioning using COMTRADE files created using industry-standard short-circuit calculation software applications. We present how each protection element can be tested and evaluated under a condition very similar to the real-world application while also reducing the cost and complexity associated with the testing procedure. The methods proposed in this paper have been utilized to create a tool that is currently utilized by a power transmission utility. The efficacy of the developed tools has been verified via lab testing and analysis. The accuracy of the generated COMTRADE files is verified via comparing with the actual fault record data. Through real-life examples from a power transmission utility, it is indicated that the developed tools can be used to avoid protection setting errors prior to or at the commissioning stage that would otherwise have not been detected. It is shown that besides reducing potential human error, the proposed method for testing can facilitate the execution of the testing procedure, thereby reducing the cost and time associated with each commissioning procedure. Comparing the labor cost associated with the commissioning process, it is indicated that the proposed method results in the labor cost reduction by 53.8%.

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