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Verifying line differential protection with time synchronised, primary end-to-end testing using a standard secondary injection test equipment

Andrea Bonetti[a], Mauro Borrielli[b], Ali Hussain[c], Niclas Wetterstrand[d]

[a]*Megger Sweden AB Stockholm, Sweden*
[b]*Megger Dallas, TX - USA*
[c]*Megger Middle East Manama, Bahrain*
[d]*Megger Group Stockholm, Sweden*

ABSTRACT

Line differential protection offers advantages over line distance protection, including simpler setting calculations. However, it relies on a communication channel between devices and cannot act as a remote backup. In protection systems, line differential protection is often used as the main protection for power lines, while line distance protection serves as a backup, especially on lower voltage levels where local redundancy is not affordable.

A new method for verifying line differential protection is presented in this paper. Unlike traditional secondary injection-based tests, this approach ensures a more complete check of the protection scheme, including CTs connection, polarity, and related relay settings. It offers a simple and comprehensive way to validate the overall protection scheme, specifically for the line differential protection. Commissioning engineers can use standard relay test sets for primary injection testing, providing confidence in the protection scheme's integrity and functionality.

Keywords: IED, GPS, state sequencer, line differential protection, relay testing, current transformer, primary injection tests, time synchronisation

1. Introduction

In a ground-breaking initiative, a power utility in the Middle East has introduced a mandatory requirement to verify the entire line protection scheme, including relay connections with the CTs, during the commissioning stage prior to energizing a transmission line. This verification process involves conducting a time-synchronized primary injection test on the primary side of the CTs. The requirement is to inject a certain current on the primary side of the CT at both ends of the line to simulate a normal load condition in the line. This means that the two instruments will inject the same current with 180° phase shift if the injection is done in accordance with Fig. 1. Due to the duration of the test, the two test devices at both line ends need to be effectively time synchronized [1–4].

This simulation enables the verification of the following:

Emails: andrea.bonetti@megger.com (Andrea Bonetti), mauro.borrielli@megger.com (Mauro Borrielli), ali.husain@megger.com (Ali Hussain), niclas.wetterstrand@megger.com (Niclas Wetterstrand)

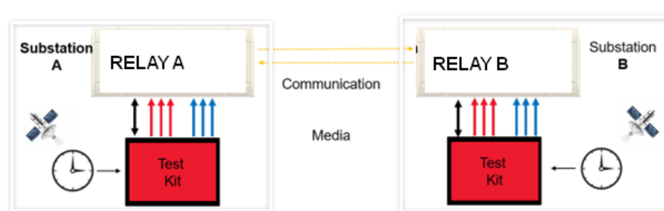


Fig. 1. Simultaneous secondary injection started by a trigger signal generated by two GNSS equipment in the two substations.

- Correct measurement of injected currents by both protection devices in terms of module and phase angle.
- Measurement of a negligible differential current (ideally zero).

Once the through load simulation is verified, a phase rotation of 180° is generated by one test set to simulate an internal fault. During this phase, the following aspects are verified:

- The protection devices measure a significant increase in the differential current, potentially leading to relay tripping based on relay settings, without a significant change in the restraining current (bias current, if this information is available at the relay HMI).

- The protection devices will show a phase shift of the phase current 180 degrees compared to the previous injection and measure the same phase currents in module.

Due to the complexity of the test setup, the minimum requirements are:

- Single phase injection of $I \geq 150$ A.
- Minimum test duration 30 minutes, to allow the test engineers located at the two substations, to comfortably carry all the necessary measurement from the relay's HMISs, take notes etc.

2. Motivations for the test

The Middle East's electrical infrastructure is rapidly expanding due to population growth, economic development, urbanization, increased electricity consumption, renewable energy initiatives, regional connections, and government investments. This surge in demand requires contractors to expand power generation and transmission capabilities, leading to time constraints during project execution. Meeting tight schedules can impact work quality and project success. One common issue during installation and commissioning is wiring errors or mistakes in relay settings, particularly related to line differential protection. The goal is to identify errors made at any stage, including with CTs, in a relatively straightforward manner.

3. Line differential protection is increasing its popularity

In medium voltage networks, often the preferred main line protection relay is often the numerical line differential protection due to its easy settings, reliability, and sensitivity. For backup, the line distance protection is activated if the communication link fails. This protection requires more expertise in setting calculations but offers the advantage of "remote backup" to control the local circuit breaker in case a remote breaker should not operate for any reason. Certain zones like underreaching and instantaneous zone 1 remain blocked during line differential protection, while time-delayed overreaching backup zones can still be active. If the communication link fails, the instantaneous underreaching zone 1 is released, providing reasonable protection for the line. This example shows the importance of line differential protection and its increasing popularity. Consequently, it becomes crucial to provide user-friendly and reliable tools and methods to commissioning engineers, thereby expediting the commissioning process and reducing the burden on them.

4. Line differential protection scheme with secondary injection tests

To test the line differential protection scheme, the relays placed at both ends of the line must receive currents from two separate test kits through secondary injection tests. However, since the instruments do not share the same phase angle reference, the so-called end-to-end test can be performed if two things are ensured:

- Both instruments can control the phase angle at the start of the test.
- They initiate the current injection simultaneously.

To achieve this simultaneity, a trigger signal with a highly accurate GNSS time source, accurate to within microseconds, is generally used (see Fig. 1). If the two test sets starts within a relative delay of 1 millisecond, a phase shift of 18 degrees (at the 50 Hz power system frequency) would be generated, and this phase shift would generated a "false differential current," in case of through load simulation, for example. To overcome this problem, a trigger signal's accuracy to be in the range of a few microseconds is used.

As the duration of this test is in general very short, in the order of few hundred of milliseconds, it is not required that the two internal clocks of the two test instruments are time synchronized to each-others: the drift generated by the different clock accuracies of the two test equipment creates a negligible phase shift within the testing time.

Currently, there are several methods in use, with the traditional one being the Go-NoGo test. This test involves a sequence of 3 states for each test set:

- Waiting for the trigger signal.
- Pre-fault state: In this state, the currents remain the same, but the angles are opposite (Figure 2, upper part) and the protection relay is not expected to operate.
- Fault state: Here, the angle at one end is rotated by 180° (see Fig. 2, bottom part). The protection relay is expected to operate.

These tests involve calculating the magnitude and phase angles of secondary currents, which accurately reflect the primary currents depicted in Fig. 2. To achieve this, the test engineer must take into account various factors, including the CT connections, their polarity (earthling points), CT ratios, and the relay settings associated with relay analog inputs. However, it is important to acknowledge that this task can be challenging and requires careful attention.

5. The primary end to end tests

The secondary injection end-to-end test excludes the CT circuits, as explained implicitly in the previous paragraph. With an end-to-end primary injection test on the CTs at the two line ends as shown in Fig. 3.

When simulating a through load condition, it is possible to verify that the two protection devices:

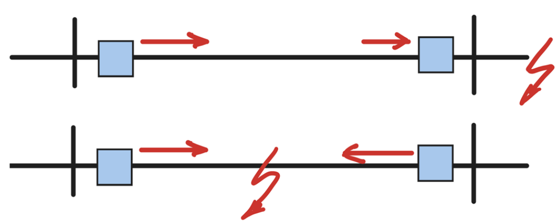


Fig. 2. Primary currents for the pre-fault and fault states for secondary injection.

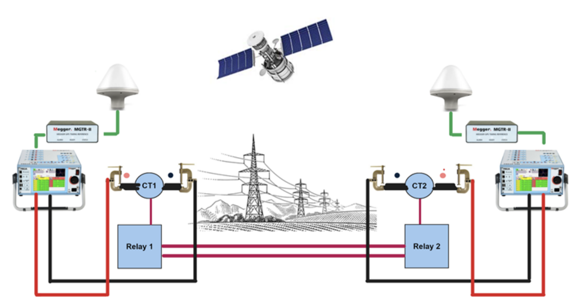


Fig. 3. Set-up and connections for the primary injection tests at both line ends.

- Accurate measurement of the injected currents.
- Measurement of identical (or similar) restraining currents.
- Measurement of negligible (if not zero) differential current. The relay is expected not to operate.

Subsequently, the test proceeds by reversing (180 degrees phase shift) the current generated at one line end to simulate an internal fault. During this phase, the line differential protection devices will measure the following:

- Accurate measurement of the injected currents.
- Measurement of identical (or similar) restraining currents.
- Measurement of a higher differential current, and depending on the relay settings, the protection relay may operate.

This comprehensive testing procedure allows an instant verification of the correctness of the CT connection, CT polarities, CT ratios, and relay settings related to analog inputs for the line differential protection. In essence, it ensures that the calculations and tests conducted with secondary injection tests are reliable from the perspective of line differential protection.

As far as the measurement is concerned, the goal is to

- Inject enough current in the CT primary side.
- Have full control of the relative phase angles between the currents injected at the two line-ends.
- Keep the current injection long enough to allow the personnel to perform the necessary measurements.

To execute this test, a few important details should be noted:

- The protection scheme should provide accurate measurements from 10% of the nominal line current, equivalent to about 10% of the CT primary ratings. For lines with a rated current around 2000 A, a test current of approximately 200 A is sufficient.
- The power utility requesting this test method deems 150 A injected on the primary side of the CT at both line ends to be more than adequate for their needs.
- The test duration should be a minimum of 30 minutes for conducting onsite measurements. This allows the operator enough time to move around the installation and verify that all devices are correctly measuring the expected currents.

The main challenges for these tests are the test set's power generation and the continuous time synchronization.

The test current must be injected through a relatively long test lead, typically ranging from 20 to 40 meters, to reach the CT terminals. Therefore, the instrument used for the test must have sufficient power to push the current through this test lead. There are units that can provide the following output characteristics (see Table 1).

Regular literature offers typical cable resistance values based on their cross-sections. Table 2 summarizes the power needed to inject 150 A into various cable lengths and cross-sections. To achieve this current level, the test lead's cross-section, which carries most of the burden, must be larger than 35 mm^2, indicated in green. Instruments with higher compliance voltage can push the current over longer distances.

Regarding time synchronization, starting the injection simultaneously based on instrument frequency accuracy poses an issue. The instruments' frequencies are not exactly the same due to crystal differences, even with high accuracy. Assuming a 2 ppm accuracy, a 50 Hz frequency corresponds to ±100 µHz. With errors in the same direction, the frequency difference is negligible, but in opposite directions, it can be up to 200 µHz. Assuming a 50 µHz difference, there will be a phase angle drift over time of 0.018°/s. If both instruments generate the frequency for 30 minutes, the relative phase angle will drift by 32.4°, leading to inconclusive test results. The small 50 µHz frequency difference makes simultaneous starting with unsynchronized clocks unsuitable. The solution is continuous synchronization with a reference clock. After achieving 1 microsecond accuracy in time synchronization, the phase shift caused by long-time injection remains constant. Any drift, like temperature-induced, is corrected through continuous time synchronization with the reference clock, which generates an accurate 1-pps signal every second, ensuring a sufficient 1 µs time accuracy for our work. This precision aligns with modern test instruments, particularly those capable of generating IEC 61850 Sampled Values, where precise clock synchronization within microseconds for protection functions utilizing phase angles are necessary.

Table 1. Instrument output characteristics.

Max current (A)	Compliance voltage (V)
6 × 32/200 VA 1 × 192/1200 VA	6.67

Table 2. Power needed to inject 150 A into various cable lengths and cross-sections.

Cross section (mm^2)	R (Ω/km)	R 2 × 40 m (mΩ)	Burden at 150 A (W)	Required voltage (V)
16	1.15	92.0	2070	13.8
25	0.727	58.2	1309	8.7
35	0.524	41.9	943	6.3
50	0.387	31.0	697	4.6
70	0.268	21.4	482	3.2

When the test instruments meet the latest requirements, the test becomes straightforward:

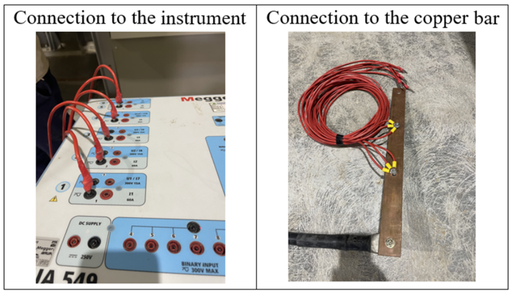
- Connect the time source to both instruments.
- Set the desired current for each line-side, for example: Side 1: 150 A @ 0° and Side 2: 150 A @ 180°.
- Start the injection at one end: the relay may operate since the other end is still at zero (dependent on relay settings).
- Start the injection at the other end, and the relay –if operated-will reset the operation.
- Continue the injection until all required measuring activities are completed.
- Stop the test at both ends.

All previously described tests can be performed with ease.

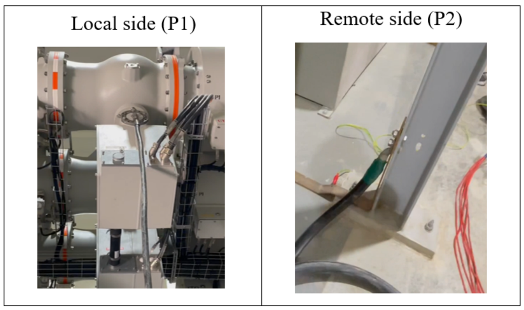
6. Field experience

With reference to the simulation of a through load, each individual current source is connected to a copper bar (see Fig. 4(a)), which is then connected to a thick cable leading to the primary side of the CT. The connections to the CT are shown in Fig. 4(b).

The current injected exceeded 180 A with a max output voltage of a few volts, as shown in Fig. 5(a). The field test was conducted on a compact GIS substation, which did not need lengthy test leads. As a result, the instrument's burden was minimized, leading to a low output voltage. Fig. 5(b) shows the measurements that were done from the relay HMIs. The measurements were successful even when



(a)



(b)

Fig. 4. Connections from the test set to the field: (a) source side and (b) CT side.

performing the test for the other phases and when simulating internal fault scenarios. This confirms that the CT connections and all related wiring were executed perfectly, resulting in a successful test field and a satisfied end user.

7. Conclusions

Including CTs in the line differential test enhances confidence in the protection circuit's proper functioning. Test systems can deliver a current of up to 5% of the nominal current (minimum 150 A) with the required compliance voltage through suitable test leads. This test serves as a final and complementary step to other secondary and primary injection tests, which verify CT polarity, CT ratio, and CT connections to the relay based on the drawings, particularly important for multifunction relays that may share CT connections for other protection functions.

References

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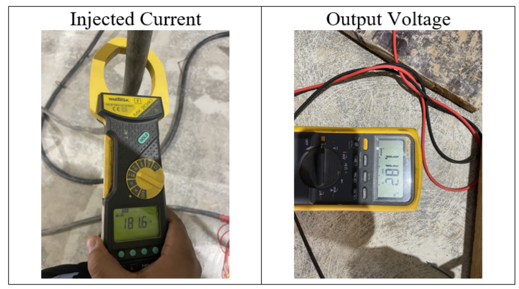
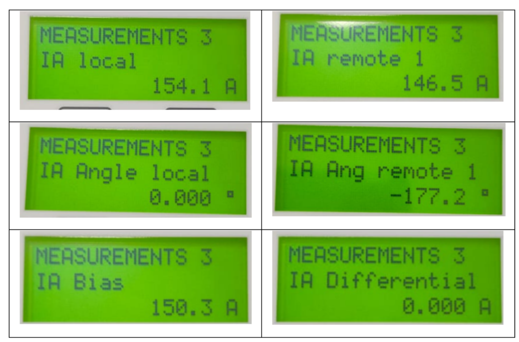


(a)



(b)

Fig. 5. Current injection: (a) injected current and (b) related voltage and measurements from relay HMIs.