Improved Possibilities for Testing of Line Differential Protection

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Introduction

Whereas testing an individual relay is quite straightforward using modern test equipment, testing distributed systems still is a challenge. A typical example of a distributed protective system is line differential protection where more than one relay is needed for the basic operation.
State-of-the-art test systems offer proper tools for the commissioning and maintenance staff to carry out this special kind of test.
Some typical approaches and practical hints for line differential relay testing are presented in this paper.

Testing Multi-End Configurations

Testing protective devices is an essential step to ensure reliable operation in the system. It is widely accepted that a proper test should be done under conditions as close to the 'real' operation as possible. One major aspect is testing the relay with settings intended for on-site operation (avoid any modifications just for ease of testing), and one major goal is to verify that the relay settings make the relay behave in the expected manner. Since the relay characteristic has a high influence on its performance under all system conditions it should be thoroughly tested. Talking about differential relays this means that all settings capable of shaping the characteristic curve should be verified.

A specific property of differential protection devices is that the supervised quantities are taken from more than one location, e.g. HV and MV side of a transformer, starpoint and busbar side of a generator winding, or both ends of a transmission line. The protection idea is to compare the phase current values of the different locations (or properties derived from them) and find out if part of them 'gets lost' in between (e.g. returning via ground or via a neighboring conductor), thus indicating an internal fault. In order to avoid tripping on measurement errors at high currents (e.g. during a through fault that is to be handled by adjacent relays) the measured differential current is biased by a stabilizing quantity, e.g. the sum of absolute current values of the monitored ends of the protected object.
In the special case of line differential protection, these ends usually are so far away from each other that the only practical protection approach is to install an individual relay at each end and make them communicate to allow current comparison and calculation of the biasing quantity. So a set of relays forms a distributed protection system. Modern systems allow more than two relays to be connected, e.g. to protect stub arrangements with three or four ends being considered as a single protected object.

This basic function and constellation allows several different approaches for line differential protection testing, each having individual pros and cons.

Single-End Injection

Since the differential relay compares the quantities of at least two ends and triggers on differences, an easy way to make it trip is to inject currents from just one side since they will be seen as 100% difference. This approach seems even more attractive for line differential relays since it circumvents the necessity to inject test signals at the remote locations, allowing a much simpler test setup.

Tempting as this approach may seem, it has the severe disadvantage of restricting the test to a single intersection between the relay characteristic and the test quantities, see **Fig. 1**. If for example the biasing quantity per phase is the sum of all current amplitudes of the protected ends (e.g. phase A current in substation 1 plus phase A current in substation 2 of a transmission line) then a test current injected from one side yields a location on a straight line with a 100% inclination in the diff vs. bias characteristic since the biasing quantity (current sum = current on injection side plus 0 on other side) is the same as the differential current. So the test will only verify this one intersection of the 100% slope with the relay characteristic. If several relay settings define the characteristics (e.g. several adjacent sections with differing slope) this test is therefore unable of verifying these settings.

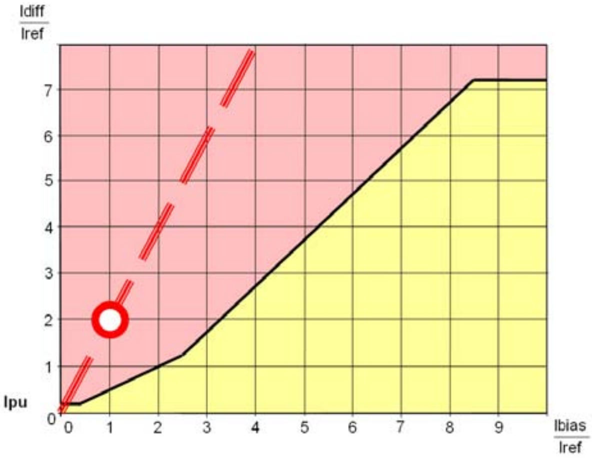


Fig. 1: Single-end infeed

This is demonstrated in **Fig. 1** where only the pickup setting Ipu can be verified but not the settable slopes to the right which have major influence on the relay performance during high fault currents.

If an individual line differential relay is to be tested without connection to its remote partner(s), numerical relays need to be switched to a dedicated test mode because otherwise the broken communication link to the remote device(s) will block relay action, or make it operate in a backup function such as overcurrent. There are two typical test modes: One simply assumes that no current is seen at the remote end(s). The test and the expected result are identical to the single infeed of a communicating relay system (see **Fig. 1**). The other one virtually mirrors its own currents as being the same as at the remote locations (loopback, e.g. connecting the communication output of one link back to its input), which results in the differential quantity (circle symbol filled in white) being a multiple of the single-infeed current (see. **Fig. 2**).

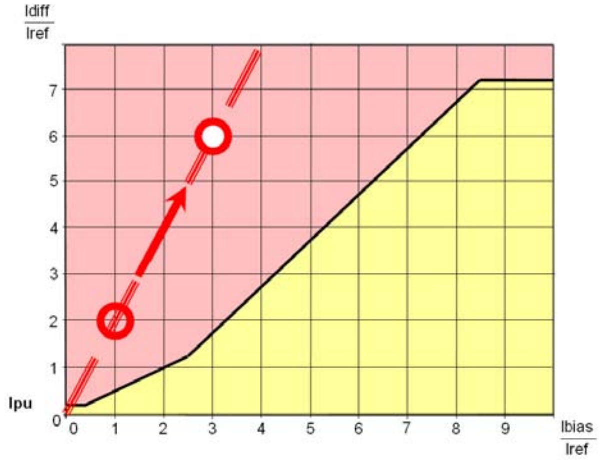


Fig. 2: Single-end infeed with relay loopback test mode

In this case, still having the same disadvantages as in **Fig. 1**, you also have to correct the found trip threshold by this multiplication factor.

Some relays, e.g. AREVA P54x, select the highest calculated biasing value of all three phases as common biasing quantity for all phases. This allows more freedom in single-sided testing since by injecting one current in one phase and a different one in another phase the higher one is taken for biasing thus allowing control over the diff/bias relation.

Local Multi-End Injection

A much more versatile way of testing is to inject the currents for all test object ends in order to simulate full primary system connection. This is the standard procedure for testing transformer differential relays with modern test equipment delivering e.g. 6 test currents, allowing full freedom to move around in the diff/bias characteristics plane, thus verifying all settings related to the characteristic. If you have local access to all line differential relays for one protected section, e.g. before mounting them on site, you can of course set up a test in the same way, i.e. set up the communication between the relays via a short local link and inject all required currents with one test device (e.g. CMC 256-6), see **Fig. 3**.

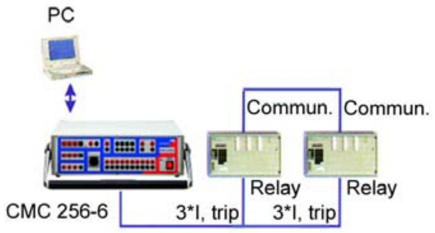


Fig. 3: Local multi-end test injection

While this approach gives a much more thorough test assessment regarding the relay settings it excludes the on-site communication channel (with possible signal delay variations the relays have to deal with) and is only possible as long as the relays are not mounted in their final (distributed) locations. It is also not possible to include the actual trip circuit in this 'test bench' setup. Therefore a separate commissioning test has to be carried out in addition.

End-to-End Testing

To allow a full on-site commissioning test, a distributed setup is required to provide all test signal injections where they are needed. But installing one test device at each end is just the first step because of the nature of the protection methods. Several approaches are known for calculating a differential quantity. Among them are comparison of the sampled values or comparison of the phasors, i.e. characteristic values of the fundamental of each monitored current. These methods require that the generated test signals at all ends must be tightly in synchronism in order to allow proper assessment by the relays well within the range of their specified tolerances. A possible setup to achieve this goal is shown in **Fig. 4**. In this setup, instead of transferring a synchronizing signal from one test device to the other(s), all are synchronized to a master clock which in fact is the time stamp transmitted by the Global Positioning System (GPS). This satellite system is mainly used for precise terrestrial localization, but for our purposes the highly accurate clock information present in the broadcasted satellite signals is used to synchronize all units without the need of direct interconnection. So each test unit is connected to a specialized GPS receiver (such as OMICRON CMGPS) and acts as a slave to the incoming time information.

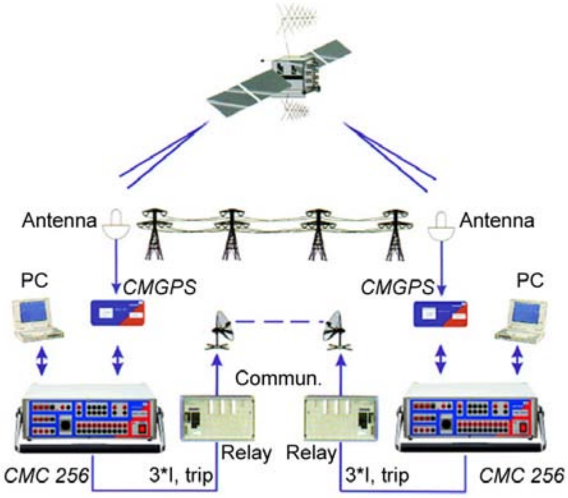


Fig. 4: End-to-end test injection

The basic concept is that whenever a test shot is to be generated, all test devices wait for a time pulse forwarded by the CMGPS units at a predefined time. This ensures highly accurate signal synchronism of all generated currents in the range of microseconds, no matter where the units are situated.

So now we have a way of generating synchronized currents. The next question is: What currents should we generate?

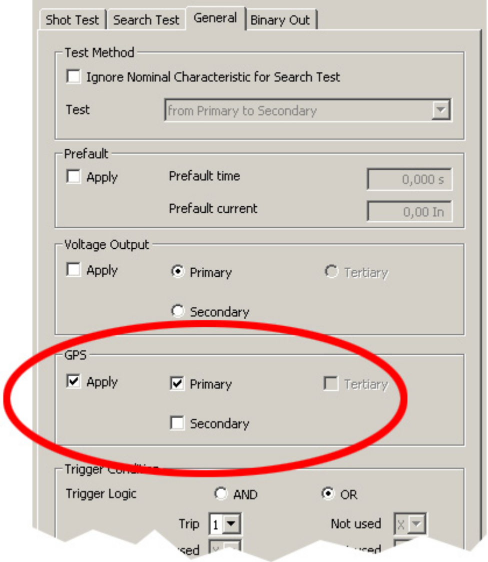
The 'classic' approach for automatic assessment of the relay reaction would be to use tools like Ramping (slowly approaching an expected threshold) or State Sequencer (generating defined states along the timeline).

This requires that you calculate the required individual phase currents for all ends for an expected trip threshold, i.e. a specific point in the characteristics plane, depending on the specific relay method (e.g. biasing) and related settings (e.g. zero sequence treatment). Once you have understood all needed relay details it would be too cumbersome to manually repeat this calculation for all shots, so some spreadsheet solution to provide the individual current values would certainly make life easier.

A more sophisticated approach is to include this relay-specific, setting-dependent calculation in the test sequence setup. For OMICRON Test Universe this means including the required test modules in an OCC container (Control Center document) and solving the calculations for this test template by making use of the scripting power provided in OCC. Some available professional solutions take this approach (like OMICRON TestBase) freeing the user from the need to deal with in-depth details of relays and scripting – the proper signals are calculated from the relay settings, hiding all internal test details from the user interface while allowing access to them if necessary.

The handiest way of course is a dedicated test module offering a tailored user interface and directly supporting synchronized test shots generating the proper phase currents for the intended differential and bias values as represented by the relay characteristic. OMICRON had recognized this need for transformer differential protection at a very early stage and offers the Advanced Differential module set, including Diff Configuration and Diff Operating Characteristic as well as Diff Trip Time Characteristic and Diff Harmonic Restraint for quite a while now. The advantage of directly working in the diff/bias plane would be great for line differential protection as well. This is why starting with Test Universe 2.11 (a free update for TU 2.0 license holders) the Configuration and the Characteristic tests now support GPS synchronization as well. The other two modules mentioned do not need to be synchronized since they only need single-end injection.

The user interface of the test modules now offers additional checkboxes to activate the GPS mode and select which current triple will be generated, see **Fig. 5**.



Test Method
☐ Ignore Nominal Characteristic for Search Test
Test: from Primary to Secondary

Prefault
☐ Apply
Prefault time: 0,000 s
Prefault current: 0,00 In

Voltage Output
☐ Apply
● Primary
○ Tertiary
○ Secondary

GPS
☑ Apply
☑ Primary
☐ Tertiary
☐ Secondary

Trigger Condition
Trigger Logic: ○ AND ● OR
Trip: 1
Not used: X

Fig. 5: Synchronous testing with Advanced Differential

Checking 'Apply' in the GPS box makes the module aware of the GPS pulses, while the checkboxes for the ends (Primary / Secondary / Tertiary) control which currents actually are generated at the location of this test device. The reason for the latter is that on one hand it would not make sense having to provide current channels for all test system currents since only some of them are needed at each location, on the other hand it might well be that more than one triple is needed on one end, e.g. if two busbar connections are located at the same substation and protected individually, or just for test purposes if you indeed have a local multiple-end setup but want to use GPS.

In order to provide maximum timing accuracy each shot is GPS-synchronized. This means that even in a Search sequence where the result is one point in the characteristic plane, each shot generated to iterate for the result waits for the next GPS pulse. Because of this it is advisable to set the pulse sequence period to a fairly short interval. Practical values are 3 to 5 seconds depending on the equipment. This means that once the test sequence is started, every 3 to 5 seconds a new shot is generated until the sequence is finished.

Setting the start time for the first pulse and the pulse sequence period is done in the CMGPS utility, either started separately from the Test Universe Start Page (under Testing Tools) or using the new 'GPS Configuration' button in the toolbar of the test module. In order to have a synchronized test start you can set the start time for the next pulse (Pulse Time and Pulse Date in CMGPS) to some time in the near future as coordinated with your partner(s) at the other end(s), e.g. 2 minutes from now, set the Pulse Rate as desired (e.g. 5 sec), exit CMPGS module (which has transferred these settings to the CMGPS hardware unit) and start the test module. As soon as the module wants to generate its first shot it will wait now until the next pulse from the CMGPS unit arrives, which will be at the predefined start time. This happens at all ends with the individual modules executing in the PCs and controlling the CMCs, ensuring a precisely synchronized shot sequence.

A practical case to consider is a sequence of test modules which are supposed to do synchronized shots, all contained in an OCC test document. Depending on the transition time from beginning the shutdown of one module to being ready after startup of the following module there is a certain chance that the PC on one end is a bit slower than the one on another end, thus possibly just missing one CMGPS pulse. The result would be that one end would generate its pulses (e.g. for a Search sequence) one pulse period earlier than the other end but would expect the other end(s) to be in sync with its own data. The relay now sees currents at its ends that really do not relate to a common test situation, so most probably will trip at the wrong instant because of a current difference resulting from different current sum assumptions in the distributed test modules. These in turn relate the trip reaction to their assumed diff/bias relation of the last shot and carry on iterating according to this result. This would inevitably lead to wrong assessment and also to diverging characteristics at the different ends. In order to avoid this it is therefore advisable to re-synchronize (i.e. redefine) the start time before the start of each test module. There are several ways to achieve this:

- Manual preselection: Before continuing with the next test module, set a new start time. The Pause module is an appropriate way to insert a break between the test modules and to inform the tester to set a new start time with the CMGPS module.
- OCC Scripting: Since the CMGPS parameters can be set using automation, the task of setting a new start time with a safety time margin can be done using the scripting language offered for the OCC environment (under View / Script View). With a Subroutine 'OnCmdTestTestAll()' the script takes over once the test is started. A sample script for this purpose is available from OMICRON.
- Dedicated OCC module: To ease this procedure without having to deal with scripting, OMICRON plans to provide a module in a future release that can be embedded in an OCC just like the Pause module and can be set up to redefine the next start time, offering the same 'click and go' comfort as the scripting solution.

These re-sync approaches can of course be applied to all GPS-aware modules in an OCC such as State Sequencer, Ramping, Pulse Ramping, NetSim and Advanced TransPlay.

Communication between Locations

The advantage of the GPS sync approach is that there is no need for a dedicated, super-fast direct trigger link between the devices. But some communication is needed to coordinate the test sequence.

At least three approaches come to mind:

- 'Classic': Each location has its own test setup (i.e. CMC, CMGPS device, and PC with Test Universe) plus a skilled operator. Each PC has the required set of OCC files that can be identical except for
  a) possibly rerouted current output channels in the Hardware Configuration section of the OCC (e.g. to route the currents of a third end to the first triple of the local CMC) and
  b) a different selection of the active current triple(s) , i.e. test end, in the GPS section of the Differential module (see above).

  Once the setup including the connection to the relay is completed, the operators call each other via stationary phone or mobile phone and agree on the first test start time to be set or, if this is done via scripting, on the start of the OCC sequence (countdown for a roughly equal start time if the true GPS start time is automatically calculated from the current time by the script. e.g. next full minute). In case of the Pause Module solution this feedback is needed whenever the next Pause module pops up.

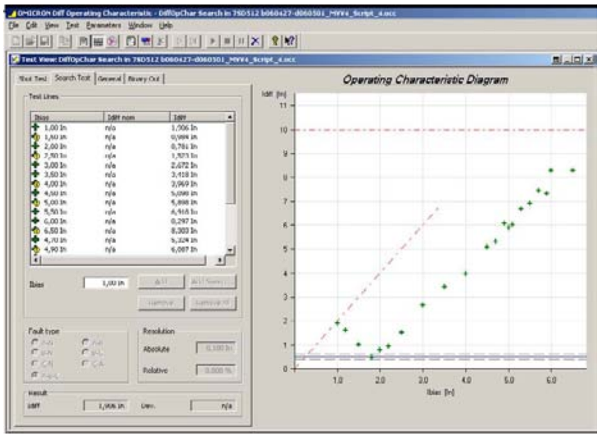
- Remote PC Control: The pre-test setup is done as above, but the PC at one end receives the desktop contents of the other PC(s) via remote control link. This could be an Ethernet connection if available, a modem connection via phone line, or even via mobile phone connection. There are diverse software products available that allow remote control of a PC, a solution is even provided within Microsoft ® Windows ® XP Professional. It is still a good idea to have a colleague stay at the remote location during the ongoing test in case anything has to be looked after, but the control of the test sequences (start time setup, monitoring of the test progress, possibly changing some module settings) is now possible from the central location. The most helpful aspect is seeing the assessed test points in the characteristics planes of all ends at the same time, allowing comparison of the results (see below).

- Remote CMC Control: With the NET-1 option of CMC 256-6 test devices it is possible to directly remote control the devices via Ethernet connection. So if there is an Ethernet infrastructure available at the substations (e.g. Wide Area Network WAN) then the controlling PCs can be situated at one location while the controlled CMCs are distributed as needed. This gives better user interface performance than the Remote PC Control solution since there are no desktop representations to transfer.

For all three described approaches the actual shots are locally synchronized, i.e. each CMC has its own CMGPS synchronizing device no matter how it is controlled from the PC user interface. So the performance of the communication network is uncritical for the real-time test sequences.

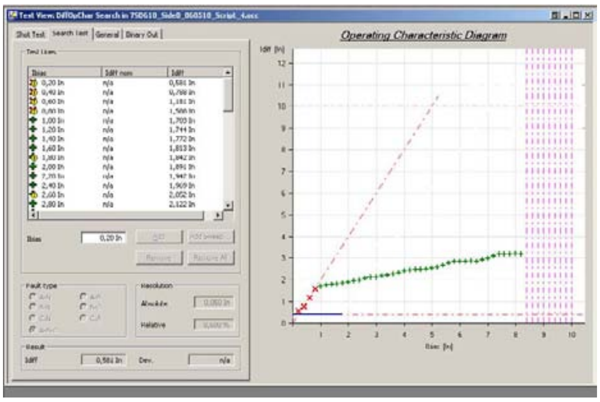
Sample Test Results

Figs. 6 and **7** show some sample results obtained during an on-site test of line differential relays. One relay pair is Siemens 7SD610 calculating biasing and difference quantities considering the CT errors, another one is 7SD512 with a different internal algorithm basically comparing the algebraic signs of the related currents under certain trigger conditions (see the related manuals).
The chosen characteristic for the diagram as shown by the Diff Operating Characteristic Module is the classic current difference vs. sum of current amplitudes representation. This makes different relay types comparable under this aspect (since this is actually what they do under these test conditions) even if they internally work with different algorithms, showing dependencies from the parameter settings which is the goal of the test. Other relays that directly use this displayed characteristic, such as AREVA PQ741, can be directly compared to the documented curves in the manufacturer's manual.



1503 I>st.state 2*I/In	1504 I>dyn 1*I/In
1505 Dyn. Clos 1.5*I/In	1508 I>allow 0.2*I/In

Fig. 6: Sample Idiff/Ibias result with 7SD512



251 K_alf/K_alf_n	1	253 E% alf/alf_n	5,0%
254 E% K_alf_n	10%	1210 I-DIFF>	2A
1213 I-DIF>sw.on	1,5A	1233 I-DIFF>>	2A

Fig. 7: Sample Idiff/Ibias result with 7SD610

Some Hints for Testing

- Trip transfer: In order to iterate to a precise trip threshold during a Search test the Diff Operating Characteristic Module needs a consistent behavior of the trip signal. This is easy for a single relay like a transformer differential relay, but for distributed relays forming a protection system it has to be ensured that all ends trip at the same time, otherwise the distributed test devices would diverge during the iteration process. So make sure that all relays use the transfer trip function to make their counterparts follow their trip signal if this is not inherent to the relay differential function.

- CB trip time: Even with transfer trip we found that common tripping does not always occur if the test currents are stopped with the recognition of the first trip signal. This is why the Diff modules now support the CB trip time from the CB Configuration block in the Test Object RIO section to prolong the test signals simulating the trip time delay of a circuit breaker. This feature is included from the same Test Universe version 2.11 as the GPS support for Diff modules, and is of course available for non-GPS tests (such as transformer) as well.

- Characteristics: Make sure to compare the characteristics as assessed by all distributed modules at the ends (i.e. in all OCCs of the parallel tests). They have to be absolutely identical (see the numerical table next to the Characteristics graph), otherwise some Search divergence happened during the test and it should be repeated (possibly with a higher setting of the GPS pulse sequence period). For this the central access to all results as outlined above is of course very handy.

- Antenna cable: The standard CMGPS delivery contains 15 m of antenna cable. While this may sound plenty it could turn out not to be sufficient in all cases under practical conditions (such as windows that are not accessible or cannot be opened, etc). So it might be a good idea to choose the 2*20 m option per CMGPS unit as offered by OMICRON to be on the safe side with 40 meters.

- Some resulting characteristics might show quite an amount of statistical 'noise'. This could well be due to the functional implementation in the relay and is no reason for concern during commissioning as long as the parameter verification is accomplished – and as long as the deviations are identical at all locations as noted above.

Conclusion

While a simple single-injection test seems an easy way to test line differential relays it offers very little information about the proper relay performance related to its settings. For on-site commissioning multiple-end injection GPS-synchronized testing is a proper way to go, as supported by the Advanced Differential Test Modules of the OMICRON Test Universe, offering test current calculation based on the test object and the characteristics plane as well as assessment results visualized in the same graphical representation.

Literature

[1] AREVA PQ 741 Relay Manual

[2] OMICRON Test Universe 2.11 Online Help

[3] Siemens 7 SD 512 Relay Manual

[4] Siemens 7 SD 610 Relay Manual