Automated Testing Of Busbar Differential Protection Using A System-Based Approach

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Abstract— Due to the high short circuit power apparent in transmission and large distribution substations, dedicated busbar protection is in use. The impact of a busbar outage leads to high requirements regarding the speed and stability of a busbar protection. As a result of different busbar topologies within substations, every configuration, and especially the logic, of the protection is unique. To guarantee accurate performance, testing the whole busbar protection during commissioning is indispensable.

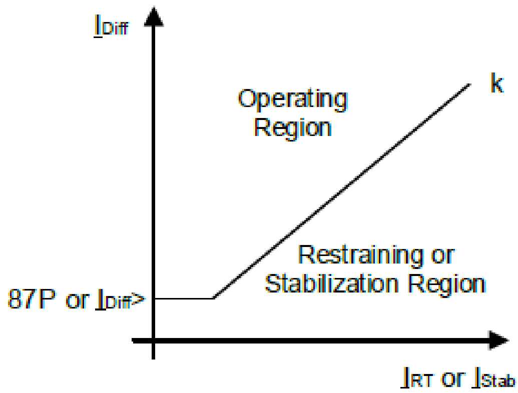
Test and verification of a busbar protection for complex busbar topologies with multiple buses, bus couplers, and bays has always been one of the most challenging tasks for commissioning. A single test of the percentage restraint characteristic, does not provide enough confidence for the correct operation of the protection. Using a system-based approach, where the whole busbar topology with all its disconnector configurations is modelled, offers new possibilities for all fault scenarios which are important to verify.

This paper will share experiences from different utilities around the world using this novel test approach and the errors that were found.

Keywords—Busbar protection testing, system-based testing

I. Testing the Differential Elements

The main protection function of a busbar protection are provided by differential elements, which apply Kirchhoff's law to identify faults within their area. The differential measurements are usually stabilized with a percentage characteristic as shown in figure 1.



$$I_{RT} = |I_1| + |I_2| \dots + |I_3|$$
$$I_{diff} = |I_1 + I_2 \dots + I_n|$$

FIGURE 1: PERCENTAGE CHARACTERISTIC

State of the art testing solutions can visualize the characteristic and by placing a shot in the plane the software module will calculate currents for the test set and afterwards assesses for trip and no-trip accordingly. The test set will inject two three-phase currents into two bay-units.

But already testing a simple percentage characteristic can become challenging with busbar protection. To achieve bus selective tripping the protection replicates the bus topology based on the disconnector position (a.k.a. disconnector or isolator replication). To maintain high security an additional check zone is applied that has to pick-up. The check zone is an additional differential element with one zone containing all bay current transformers (CT). The check zone is independent of the disconnector replication [1]. To avoid over-stabilization a check-zone applies special logic to choose the restraining quantity requiring a special test setup , where one three phase current is looped through two bays and a second injects current to a third bay [2]. Also the bus selective element and the check zone element overlap. To easily test each characteristic settings are changed, elements

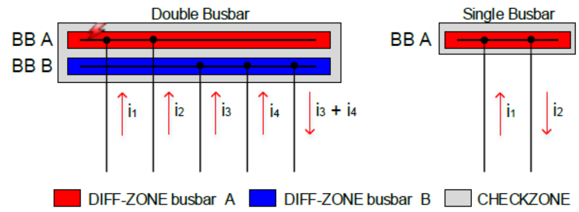


FIGURE 2 DIFFERENT BUSBAR ZONES

are disabled or test contacts are used during test. We consider this as a very dangerous and questionable approach. There is a potential risk of leaving the protection in an inconsistent state or bypassing the actual protection logic that will be in operation.

So far such settings-based test can verify, that the element and relay is working correct according to the given settings. Stopping to test here would fall short of the complexity of modern busbar protection. Special attention is required when testing:

- Logic functions e.g. breaker failure (BF) and dead zone fault detection
- Correct configuration of the disconnector replication
- The overall protection incl. all functions are working together
- All current inputs are working with the right CT ratio.
- Coordination with bay, feeder and backup protection

Potential issues in these areas are usually classified as logic, settings and design errors. As studies prove [3] that for any protection this is the most common cause for errors. As testing protection always has to find the right balance between depth and resources, it is important to put the effort in testing where errors are most likely. Therefor we suggest a system-based test as an integral part of busbar testing.

II. SYSTEM-BASED TESTING

A setting-based test verifies elements and functions of a relay according to the given settings. Contrary a system-based test validates if the protection system is working correctly under real power system conditions. Instead of testing a characteristic with a steady-state output, faults (or other system conditions) are calculated with a power system simulation and directly outputted. This way it is tested that the protection system with its logic and settings are actually working for the power system they have been designed for. Additionally a system-based test saves a lot of time during preparation, execution and troubleshooting of a test, as we will see in the following paragraphs.

Due to all the possible busbar topologies, almost every application of a busbar protection system is unique. Thus there is no standard way of testing the disconnector replication and other logics. To correctly operate, the busbar protection needs to know the topology and disconnector position for all bays, sectionalizers and couplers during operation. Therefor a test system has to mimic the whole busbar power system with all the binary information of the disconnector states and the different bay currents in a consistent manner. Consistent means, that the analogue values are plausible, for example that a current is only measured when the within the corresponding current path all disconnectors circuit breakers are closed. Otherwise functions like measurement supervision, disconnector supervision and breaker failure functions will prevent the protection from working as under real world conditions and fail the test.

Ideally current is injected into all bays simultaneously, but depending on the amount of bays and the available test sets, this is not always feasible. But already two six phase test sets can feed into three feeder bays and one coupling bay, enabling to run almost all important test cases. After all feeder bays have successfully passed, the test sets can be connected to next bay units. Depending on the substation design and in case of a distributed protection, the bay units may be several meters apart from each other. This results in the key features of a test system:

- Simulation of disconnector states.
- Calculation of all test set currents, for each test step and each state in the test sequence.
- Controlling multiple time synchronized test sets.

Without a system-based test solution this is often achieved by setting up a spreadsheet. Each row or test step has multiple columns defining disconnector states and bay currents. When executing, the disconnector positions are mimicked according to the current row by bridging the binary contacts at the bay units or with a custom made switchboard. The currents are transferred to one or more sequencer files in case of multiple test sets. Creating such a spreadsheet and making it executable can be very time consuming. The effort is growing exponentially with the size of the bus. A non-technical issue is that these spreadsheets are not very comprehensible. Usually they are prepared by a test engineer transforming a real world scenario into a spreadsheet row. If the technician in the field is a different person and tries to understand the test step row, he transforms the spreadsheet back into a real world scenario in his mind. This permanent mind mapping is inefficient and a potential source of error.

A system-based testing tool can be an all in one solution to this. To model the power system the bus topology, including the CT ratios and ideally the short circuit currents of the feeders, can be edited with a single line editor. Everything to define a test step can now be done within the single-line.

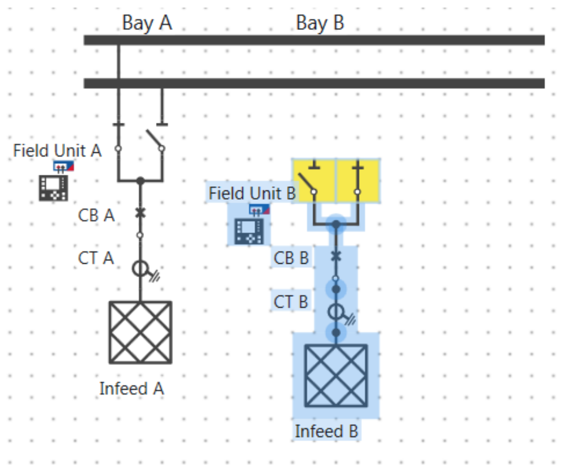


FIGURE 3: SINGLE LINE EDITOR

A. Disconnector simulation

Within a test case the disconnectors can be operated directly in the editor. That way the power system simulation will simulate the correct current sharing. Additionally a system-based test solution can map the double bit position of the disconnector to binary outputs of the test set. Before a test step is executed, the SW will set all binary outputs of the test set according to the defined disconnector position. This way, the test can be fully automated without the need to manually bridge disconnector contact before every test step, reducing the source of errors and increasing efficiency. If all disconnectors are simulated by the test solution, many outputs will be required. Therefor some test set can easily be extended with binary outputs at a fraction of the costs of an additional test set.

B. Current Calculation

The current calculation is almost effortless and constant, no matter how complex the topology is. By changing the load flow, placing faults and adding breaker events within the SW, the power system simulation calculates the current samples for all CT locations in one go.

C. Working with multiple test sets simultaneously

When the currents signals have been calculated, they get transferred to one or multiple test sets. Afterwards the SW sets a start time for execution. As all test sets are time synchronized, they will start execution at the same time. After execution the test sets will send back the measured binary events to the SW, where they can be assessed. All these steps can be controlled by one SW and start with a simple click on the execute button. There is no user coordination or separate test document per test set required.

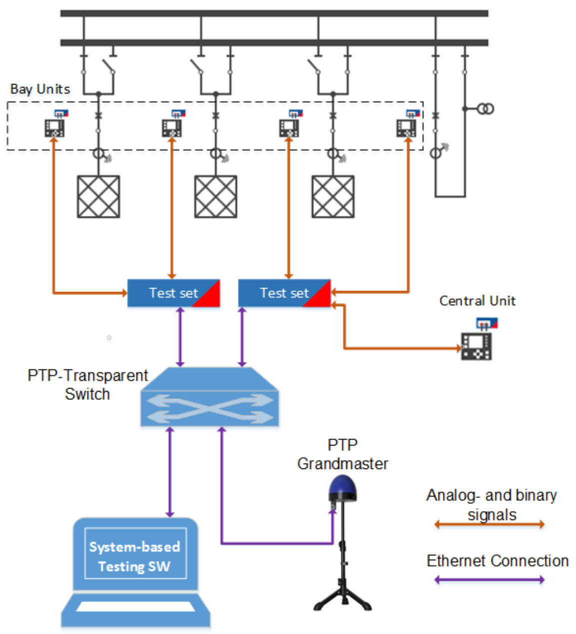


FIGURE 4 TEST SETUP FOR A SYSTEM-BASED BUSBAR PROTECTION TEST

Time synchronization is required, when working with multiple test sets. Every time delay in execution will result in a phase shift between the test set currents, which can ultimately trip the differential element even under normal load flow. To avoid the tedious setup of a GPS Antenna for every single test set, the test sets can be connected to a PTP enabled Ethernet network. This setup only requires one reference PTP master time source connected to a special switch (transparent clock). From there the time is distributed to all test sets. At the same time this network can be used to communicate between the system-based test software and the test sets.

D. Testing complex logic sequences

In many test steps it is important to react to the protection commands. When a trip command is sent, the breaker has to open within the simulation and no current flow must be simulated. Again the simulation must be consistent again. If this is not the case, it would be considered as a breaker failure and logic that would become active after the first trip cannot be executed. The capability of a simulation to react to a command of the system under test is usually called real-time closed-loop. But real-time simulation systems are only suitable for the lab, require expert knowledge and a high investment, while test sets can be distributed. A suitable alternative to hard real time is to use of an iterative closed-loop algorithm. When applying this algorithm to a simulation with a busbar fault, the first iteration gets injected without any CB commands. Nonetheless, the protection will respond to the fault with a trip command which is recorded by the test software. Because we assume that the relay should respond with the same trip time under the same current waveform as in the previous injection, we will inject the same current waveform from start followed by a breaker open event, shortly after the expected trip. When another trip or close command is sent, that has not been part of the previous simulations, a third iteration is executed now including two breaker events. This algorithm continues till no new unknown trip or close command has been sent by the protection. The last iteration then achieves a similar result as a real-time simulator. The benefit in using this is the simplicity when testing logic. After placing the fault, the iterative closed-loop will take over. Figure 5 shows an example with two iterations.

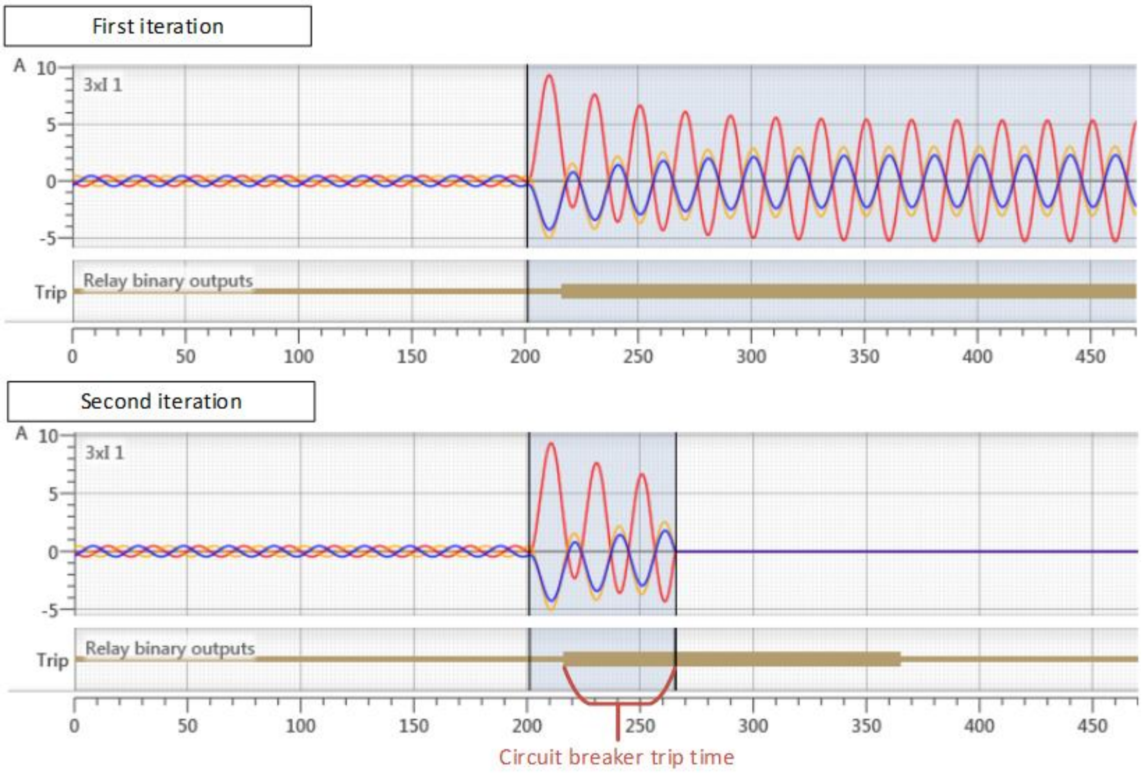


FIGURE 5: EXEMPLARY ITERATIVE CLOSED-LOOP SEQUENCE

III. REAL WORLD EXPERIENCE

Over the last three years we gathered a lot of experiences testing busbar protection with a dedicated system-based testing solution as written in detail in [4] and [5]. In this paper we wanted to emphasize the importance of system-based testing, so we summarized a few errors that were found during several field and factory tests. In most cases the system-based approach was used the very first time by the test engineer or technician, which is why often the protection was already tested with their well-established testing tools and methods. So it can be said that most of the errors would have not been found without the system-based testing tool. In retrospective all errors we describe here can also be found with traditional testing tools, but we experienced that the simplicity of a dedicated system-based test solution positively influences the quality. When creating and running a test case is as easy as just dragging a fault and pressing execute, testers are performing more tests with more depth.

A. Error in dead zone

For 100% selectivity in coupling bays usually two CTs on each side of the CB are installed, so that the bus selective zones overlap. Often for economic reasons only one CT is

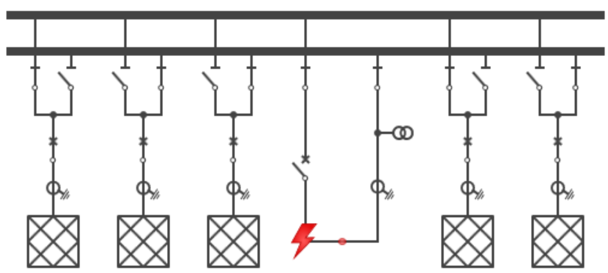


FIGURE 6: FAULT IN DEAD-ZONE

installed which creates a so called dead-zone between the CT and CB. Modern busbar protection has special logic to detect faults within the dead zone, by measuring the coupling CB status bits. For the commissioning of a busbar protection for a double bus topology, a test case was defined that should validate, that a fault in the dead zone while the coupling CB was open, lead to an instantaneous trip of bus B only. (If the CB would be closed, bus A would trip, followed by bus b). The protection tripped unselectively within the test. The error was resolved within the settings of the busbar protection.

B. *Two field units in coupling bay*

The following error was found in a distributed busbar protection for a double bus topology with an additional transfer bus. Because of limited inputs on the first bay unit a second bay unit was installed in the coupling bay. During commissioning, the test cases with dead-zone faults initially failed. Due to the configuration both bay units had to provide CB status bits, but only one bay unit was wired to the CB status contacts. The issue was resolved by wiring the CB status contacts also to the second unit.

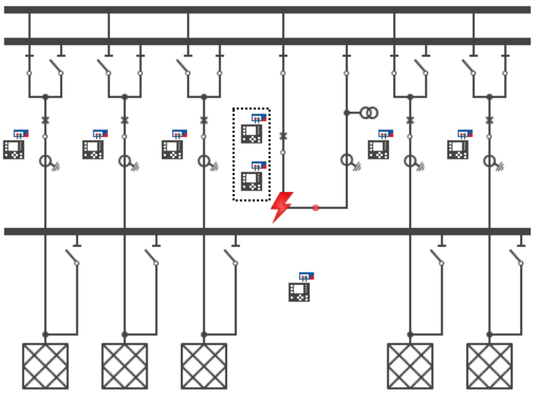


FIGURE 7: TWO BAY UNITS IN COUPLING BAY

C. *Unwanted trip on BF command*

This following error was discovered during the validation of a protection concept in a testing lab. The system under test consisted of a low impedance busbar protection and the dedicated feeder protection relays. Within the test case a fault outside of the differential zone was simulated. While this fault should be handled by the feeder protection, the busbar protection immediately starts an internal BF timer on feeder pick up. Because the system-based test also simulated the CB trip delay, it was discovered that there was not enough security margin in the BF timer setting, which could lead to an unselective trip of the busbar.

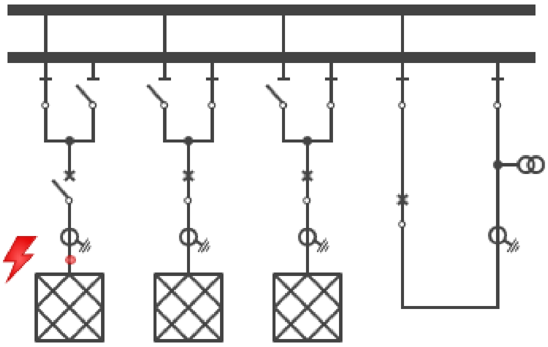


FIGURE 8: OUTSIDE FAULT

D. *Incorrectly wired neutral current input*

The following error was discovered in a busbar protection for a double busbar in a distributed network. The power system was operated with low impedance grounding, leading to small currents for phase to ground faults. Within the default differential element such a small fault current would be over-restrained with the full three phase load current. The utility addressed this issue by choosing a busbar protection with a dedicated percentage restraint characteristic for neutral current (I_N). The I_N was measured via separate current input connected to a Holmgreen circuit. A system-based test case showed, that external phase to ground faults caused an unselective busbar trip. This was caused by the wrong polarity of the I_N current input. Previous non system-based test, did not uncover this error as only each bay was tested with a single current injection.

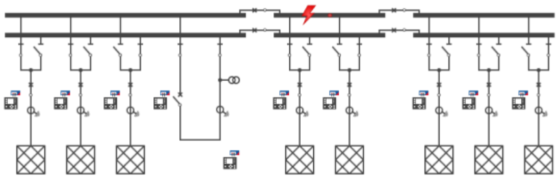


FIGURE 9: BUS FAULT ON MIDDLE SECTION

IV. CONCLUSION

The errors found in the field proved, that system testing is a necessity in testing modern busbar protection. A dedicated system-based testing solution greatly simplifies performing such tests.

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