Relay Protection and Substation Automation of Modern Power Systems
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S1-10: New and re-discovered theories and practices in relay protection

Design principles of high performance numerical busbar differential protection

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Introduction

For busbar protection applications, it is extremely important to have good security since an unwanted operation might have severe consequences. The unwanted operation of the bus differential relay will have the similar effect as simultaneous faults on all power system elements connected to the bus. On the other hand, the relay has to be dependable as well. Failure to operate or even slow operation of the differential relay, in case of an actual internal fault, can have fatal consequences. Human injuries, power system blackout, transient instability or considerable damage to the surrounding substation equipment and the close-by generators are some of the possible outcomes. These two main requirements are contradictory to each other in nature. To design the differential relay to satisfy these two requirements at the same time is not an easy task.

Design Principles

The basic concept for any bus differential relay is practically a direct use of Kirchoff's first law that the sum of all currents connected to one differential protection zone shall be zero. If that is not the case, an internal fault has occurred.

In other words, as seen by the busbar differential protection the sum of all currents which flow into the protection zone (i.e. currents with positive value) must be equal to the sum of all currents that flow out of the protection zone (i.e. currents with negative value), at any instant of time. Such interpretation enables quite efficient implementation of a numerical bus differential relay algorithm, because any differential zone can be represented by just three quantities, as shown in Figure 1, regardless the number of actually connected feeders.

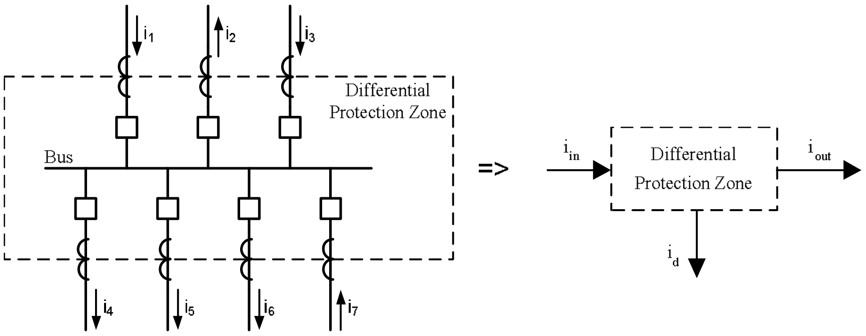


Figure 1: Representation of the bus differential protection zone

Where:

- i_{in} is total instantaneous incoming current flowing into the bus
- i_{out} is total instantaneous outgoing current flowing from the bus
- i_d is instantaneous differential current

Basics of differential algorithm calculations

The calculation of these three relevant quantities from the CT input values are performed by numerical busbar differential protection algorithm. These calculations are completely phase-segregated therefore they will be explained for one phase only. Calculations for the other two phases are done in exactly the same way. The pre-requests for correct calculations are:

- Sampling of all analogue current inputs have to be done simultaneously
- Current samples have to be in primary amperes
- All currents connected to the zone have to be measured with same reference direction (i.e. all towards the zone or all from the zone).

First the instantaneous differential current is calculated as absolute value of the sum of all currents connected to the protection zone:

$$i_d = \left| \sum_{j=1}^{N} i_j \right| \tag{1.1}$$

where:

- i_d instantaneous differential current (calculated from raw samples)
- N total number of bays connected to the protection zone
- i_j instantaneous current value (i.e. latest sample value) from bay j

Then only the sum of all latest current samples with positive value is made:

$$SP = \sum_{j=1}^{M} i_j \qquad (i_j \geq 0) \tag{1.2}$$

where:

- M number of bays with positive current sample value at the latest sampling instant (M<N)

as well as the absolute value of the sum of all latest current samples with negative value:

$$SN = \left| \sum_{j=M+1}^{N} i_j \right| \qquad (i_j < 0) \tag{1.3}$$

Finally the instantaneous incoming and outgoing currents are calculated as follows:

$$i_{in} = \max\{SP, SN\} \tag{1.4}$$

$$i_{out} = \min\{SP, SN\} \tag{1.5}$$

Note that due to such calculations the following will always be true:

- these three quantities are calculated by using raw samples from all bay currents connected to the busbar (e.g. 20 times per power system cycle)
- these three quantities (i.e. i_{in}, i_{out} and i_d) will be of a "DC" nature in time (i.e. these three quantities can only have a positive numerical value). This means that the instantaneous incoming and outgoing currents during normal load condition looks like as the output of the full wave rectifier;
- i_{in} is always bigger than or equal to i_{out};
- during normal through load conditions the total instantaneous incoming current will be equal to the total instantaneous outgoing current and differential current is negligible; and
- any differential protection zone can be represented as shown in Figure 1, regardless the number of the bays connected to the bus.

The instantaneous quantities are constantly changing in time; therefore RMS values of the incoming, outgoing and differential currents (i.e. I_{IN}, I_{OUT} and I_D respectively) as well as they rate of change are used in the algorithm as well. These quantities are calculated over last power system cycle (i.e. 20ms long, moving window for 50Hz system) by using numerical integration. Only the formula for I_{IN} will be presented here (the other two RMS quantities are calculated by using the same principle)

$$I_{IN} = \frac{1}{T} \cdot \int_{-T}^{0} i_{in} \partial t \approx k \cdot \sum_{1}^{20} i_{in} \tag{1.6}$$

where

- T is the length of one fundamental power system cycle (e.g. 20ms for 50Hz power system)
- $\sum_{1}^{20} i_{in}$ is a sum of instantaneous incoming currents sample values over the last power system cycle (equation is shown when 20 samples in power system cycle are used)
- k is a constant in the algorithm (e.g. gain) which properly scale this sum to the corresponding RMS magnitude value

Differential Protection Algorithm

When all six values (i.e. i_{in}, i_{out}, i_d, I_{IN}, I_{OUT} and I_D) are calculated, they are passed further to the differential protection and algorithm for further processing. In the following sections the behavior of the algorithm for different operating conditions will be presented. The disturbance in all presented cases will happen at sample number 41.

Algorithm operation during internal fault

When solid internal fault happens (at sample 41 on Figure 2) voltage of the faulty phase collapses to zero. All active bays will instantly start to feed the fault current towards the faulty bus. This means that instantaneous incoming current will sharply increase while the instantaneous outgoing current will become practically zero as shown in Figure 2. At the same time the RMS values of these two quantities will split from each other at the moment when internal fault happens. The RMS value of the incoming current will sharply rise towards the new value determined by the fault current level, while the RMS values of the outgoing current will decrease towards to zero value. This sudden split of the two RMS quantities indicates the internal fault. Thus, the busbar protection waits for differential current to exceed the set minimal pickup value and then the trip signal from the busbar differential protection is given. Graphs of all these values during internal fault are shown in Figure 2. By using this principle fast operating time in order of half a cycle are achieved for most internal faults.

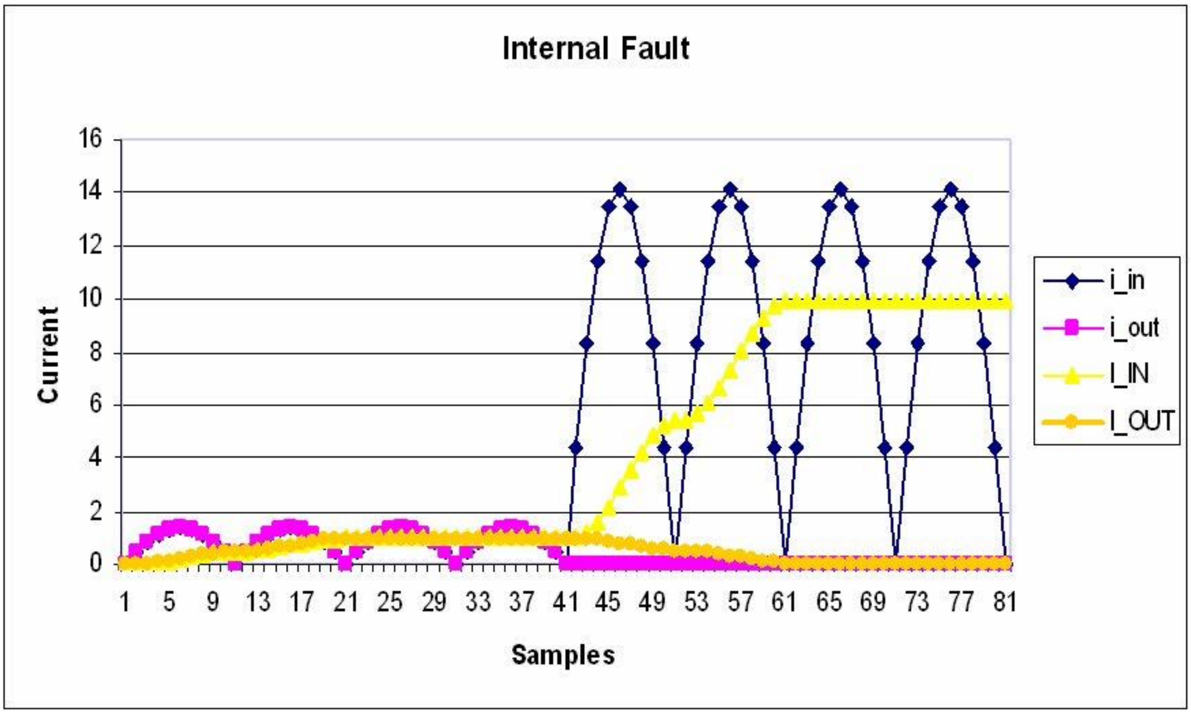


Figure 2: Behavior of the calculated quantities during internal fault

Algorithm operation during external fault followed by CT saturation

When heavy external fault happens (at sample 41 on Figure 3) quite big thorough-going current will start to flow through the protected busbar. This can cause quite fast saturation of some of the CTs connected to the busbar protection. Typically the CT in the faulty feeder will saturate first, but this might not always be the case. However, before any CT saturation the instantaneous incoming and outgoing currents will be the same as shown in Figure 3. Nevertheless once the first CT saturate these two quantities will be the same only during the short period of time after the primary fault current zero crossing (i.e. before any CT saturate again). At the same time the RMS values of these two quantities will rise sharply and together immediately after the fault inception, but as soon as any of the CTs connected to the busbar protection becomes saturated these two RMS quantities will have quite different values. Thus the RMS values can be just used at the beginning of the external fault in order to detect that the fault is external. However, during the external fault no good tripping criterion can be done by using the RMS values due to a fact that they will be corrupted due to CT saturation. In order to remain stable for such external faults the relay actually checks that after every fault current zero crossing there is a short period of time (e.g. 2ms) during which the instantaneous values of the incoming and outgoing currents are the same. If this is the case relay just simply waits for the following fault current zero crossing in order to make new tripping decision. By doing so the algorithm remains stable for all external faults but at the same time relay is not blocked and it will operate for all evolving faults.

Algorithm behavior during open CT conditions

At the moment when anyone of the connected CTs to the busbar protection becomes open- or short-circuited by any error in the CT secondary circuit the differential protection sees this as loss of outgoing current value (e.g. due to equation (1.5)). As a result the RMS value of the incoming current remains unchanged while at the same time the RMS value of the outgoing currents is going down towards the new value. When such behavior of the RMS quantities is detected the differential algorithm just waits until the differential current exceeds the pre-set value for open CT detection and at that point of time the affected phase of that differential zone is either instantly blocked or just de-sensitized. Thus, the differential protection remains stable for such errors in CT secondary circuit.

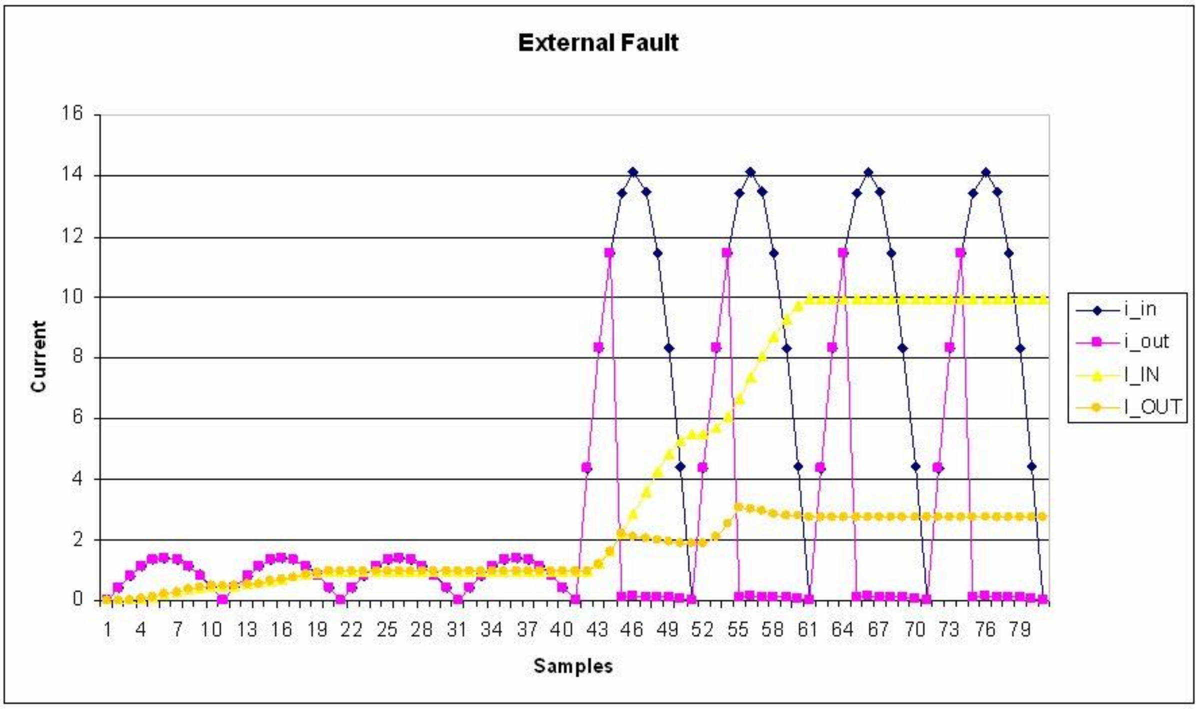


Figure 3: Behavior of the calculated quantities during external fault

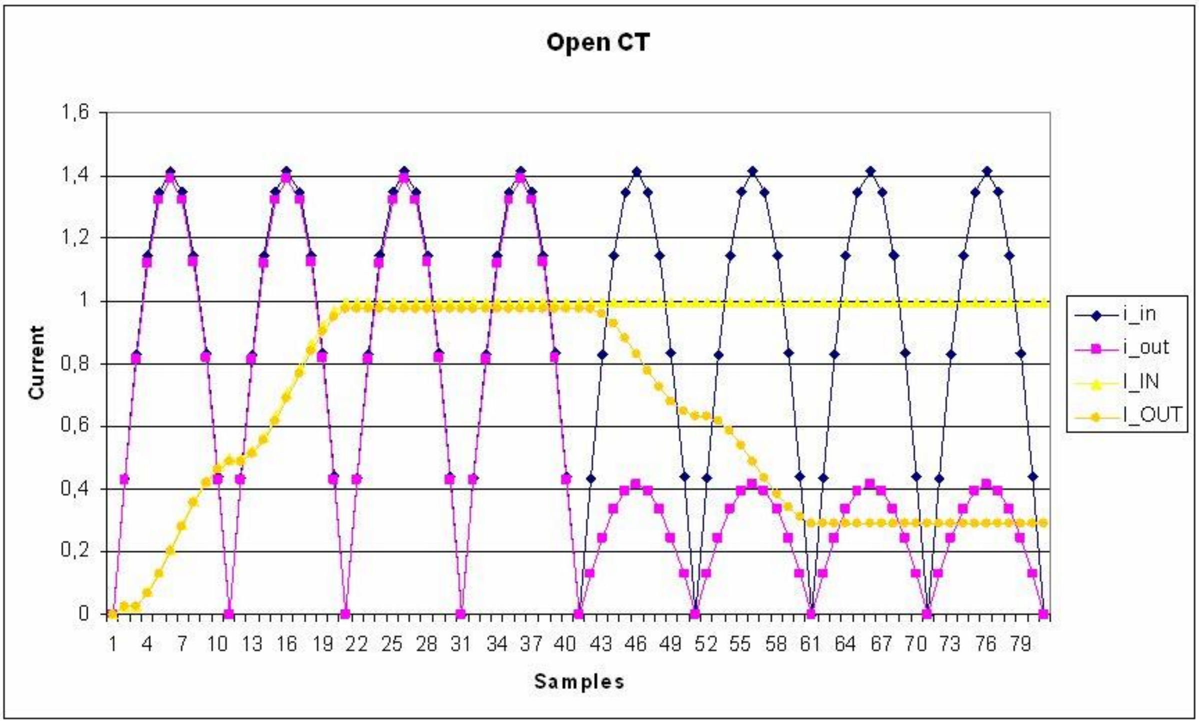
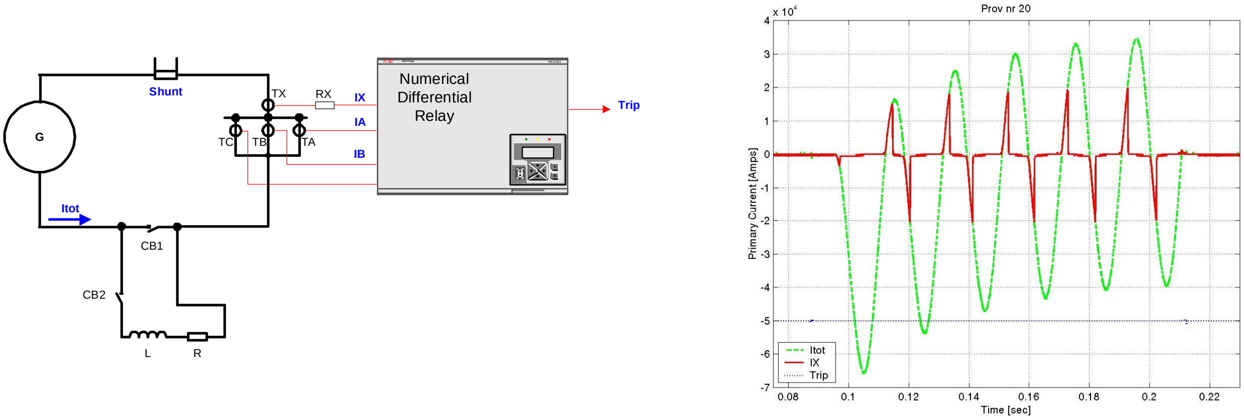


Figure 4: Behavior of the calculated quantities during open CT conditions

Testing of the Differential Protection Algorithm

This differential algorithm has been tested in the power laboratory and different analogue or digital power system simulators. All tests shows excellent result of this algorithm. In this section first the testing in the High-Power laboratory will be presented. During testing of external faults the test circuit was arranged as shown in Figure 5a. During these tests a primary current level of 26kA RMS was used. The total incoming current to the differential relay was supplied to the numerical protection relay via three parallel-connected current transformers (TA, TB and TC). However, the total outgoing current from the differential zone was supplied to the numerical protection relay via only one weak current transformer TX. Therefore, during the external fault, the measured current IX on the secondary side of the current transformer TX had to balance the differential relay and prevent any unwanted operation.The CT data were:

- TA, TB and TC CTs: 400/1; 5P20; 20VA with very low external burden
- TX CT: 200/1; 5P20; 10VA with external additional burden RX



a) b)

Figure 5: Testing in High-Power Laboratory

In test case presented in Figure 5b, the current transformer TX was pre-magnetized with the dc current in order to get maximum possible remanence. Resistance RX had a value of 30Ω and the fault was applied without any pre load. The switching angle was chosen to get the maximum possible dc offset of the fault current. The first peak value of the primary current was 65kA. Current transformer TX saturated within 1.2 ms in the first power system cycle, but the numerical differential relay remained fully stable as can be seen from Figure 5b.

The relay was as well tested in the independent testing institute. Among other thinks the relay was tested for its behavior during evolving faults, as presented in Figure 6. The three feeders were connected to this differential zone during this test.

First the external fault followed by CT saturation has been applied to the relay. The relay remained stable as shown in Figure 6. After 40ms the internal fault in the same phase has been applied. The relay detected that the fault has evolved from external fault to internal fault and it has given the trip command to all CBs connected to the faulty bus as shown in Figure 6.

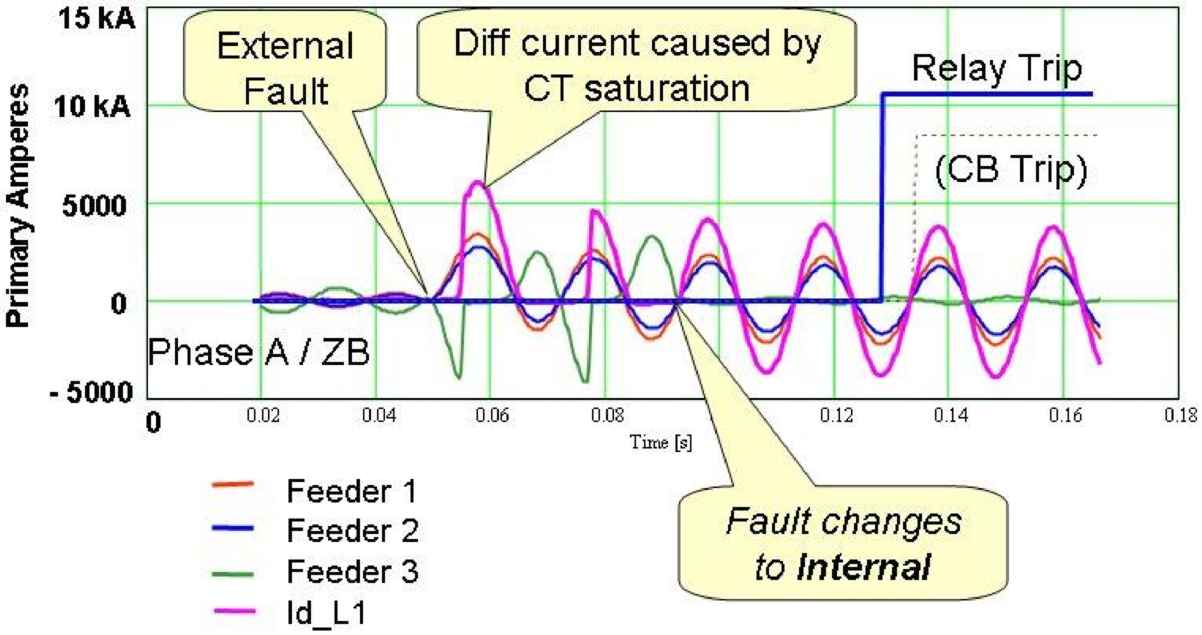


Figure 6: Testing in CEPRI Laboratory

Conclusion

In this paper it has been shown that by looking into the property of only three quantities it is possible to make a numerical busbar differential protection relay which can:

- Operate quickly for internal faults due to the fact that i_{in} becomes much larger than i_{out} during an internal fault (i.e. current flows into the faulty bus but it doesn't flow out from the faulty bus)
- Remain stable for external faults followed by CT saturation due to a fact that for short period of time, immediately after the fault current zero crossing, i_{in} will be equal to i_{out} (i.e. before any CT goes into saturation)
- Detect an open CT secondary circuit in any one of the connected feeder CTs when one of i_{in} or i_{out} remain unchanged while the other experiences a sudden drop in magnitude

These are actually the very similar methods used by analogue, moderate impedance bus differential relay which has been successfully used in practice for many years [1], [2].

This numerical algorithm has been used in two generation of the numerical busbar differential protections [4] and [5] with excellent performance in actual installations for busbar protections for power system buses of up to and including 750kV voltage level.

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