

# Modern Design Principles for Numerical Busbar Differential Protection

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## Summary

For busbar protection, 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. These two requirements are contradictory to each other. To design the differential relay to satisfy both requirements at the same time is not an easy task.

Busbar protection shall also be able to dynamically include and/or exclude individual bay currents from differential zones. Therefore it must contain so-called dynamic zone selection in order to adapt to changing topology of substation for multi-zone applications. The software based dynamic zone selection ensures:

1. Dynamic linking of measured bay currents to the appropriate differential protection zone(s) as required by substation topology. Efficient merging of differential zones when required by substation topology (that is, zone interconnection or load-transfer).
2. Easy zone merging initiated externally by closing of bus-sectionalizing disconnectors.
3. Selective operation of busbar differential protection to ensure tripping only of circuit breakers connected to the faulty zone.
4. Selective tripping for circuit breaker failure protection.
5. Correct marshaling of backup-trip commands from internally integrated or external circuit breaker failure protections to all surrounding circuit breakers.

6. Easy incorporation of bus-section and/or bus-coupler bays (that is, tie-breakers) with one or two sets of CTs into the protection scheme.

7. Disconnecter and/or circuit breaker status supervision.

Modern design for a Busbar Differential Protection IED [10] containing six differential protection zones and fulfilling all of the above mentioned requirements will be presented in the paper.

## Keywords

Busbar Protection, Differential Protection, Dynamic Zone Selection.

## I INTRODUCTION

The bus zone protection has experienced several decades of changes. It is fair to say that the first introduction of bus zone protection in Europe started in Britain as early as 1904. This was known as the circulating current Merz-Price system [7]. Later, in the beginning of the 1940s, the high impedance differential protection scheme was introduced [1]. One of the main features of the high impedance differential scheme is that it permits the faulty line current transformer (CT) to be fully saturated in the event of a severe external fault and still keep the stability. However, in order to fulfil this requirement, it demands that all CT cores connected to one protection zone have to have the same ratio and the same magnetizing characteristics.

As a result of the requirements from central Europe to cope with different CT ratios within one protection zone, the percentage restrained differential protection scheme, based on a special analog circuit, was developed in the late 1960s [2].

Although successful in practice, both of the above mentioned analog differential relays have some shortcomings such as the need for auxiliary CTs to match the different CT ratios, the lack of self-supervision, secondary CT switching for double or multiple busbar arrangements and relatively complicated scheme engineering.

## II PRINCIPLES OF DIFFERENTIAL PROTECTION

The basic concept for any bus differential relay is that the sum of all currents, which flow into the protection zone, must be equal to the sum of all currents, which flow out of the protection zone. If that is not the case, an internal fault has occurred. This is practically a direct use of Kirchhoff's first law, which is taught in the "Basics of Electricity" during the first year of electrical engineering studies. Unfortunately, practice is often different and more difficult than the theory in the books.

### Magnetic core current transformers

Bus differential relays do not measure directly the primary current in the high voltage conductors, but instead the secondary current from magnetic cores positioned inside CTs, which are installed in all high-voltage bays. Because the current transformer is a non-linear measuring device, under high current conditions in the primary CT circuit the secondary CT current can be drastically different from the original primary current.

This is caused by CT saturation, a phenomenon that is well known to protection engineers [6]. It is especially relevant for bus differential protection applications, because it has the tendency to cause unwanted operation of the differential relay.

Remanence in the magnetic core of a current transformer is an additional factor, which can influence the secondary CT current. It can improve or reduce the capability of the current transformer to properly transfer the primary current to the secondary side. However the CT remanence is a random parameter and it is not possible in practice to precisely determine it.

### Analog differential protection

The high impedance differential relay generally solves all practical problems caused by the CT non-linear characteristics by using the galvanic connection between the secondary circuits of all CTs connected to the protected zone. The scheme is designed in such a way that the current distribution through the differential branch during all transient conditions caused by nonlinearity of the CTs will not cause the unwanted operation of the differential relay. This is achieved by connecting a high impedance (usually resistance) in series with the operating element of the differential relay. This impedance will then limit the level of false differential current through the differential branch. To obtain the optimum relay performance, the resistive burden in the individual CT secondary circuits must be kept low and should have a similar value in all bays.

At the same time no other relays can be connected to the same CT core. Due to the lack of any restraint quantity, it is strongly required that all current transformers within one differential zone have to have the same ratio and the same magnetizing characteristic. All these requirements impose additional expense to the power utility in order to purchase specially made CT cores used for the bus differential protection only. However if all of the above conditions are met, this scheme is quite reliable and very sensitive. Its usual operating times for internal faults are below one power system cycle [1].

The percentage restrained differential protection scheme [2], based on a special analog circuit, also depends on the galvanic connection between the secondary circuits of all CTs, connected to the protected zone, to remain stable for all transient conditions caused by the non-linearity of the main CTs. The galvanic connection is made via a special diode circuit arrangement, as shown in Figure 1. This diode circuit creates the rectified incoming current  $I_{T3}$  and the rectified outgoing current  $I_L$ . The difference between these two currents is the differential current  $I_{d1}$ . By this approach, a very simple but effective design of the relay is obtained. All relay decisions are based only on these three quantities, and the operation of the relay does not depend on the number of connected HV bays to the protection zone.

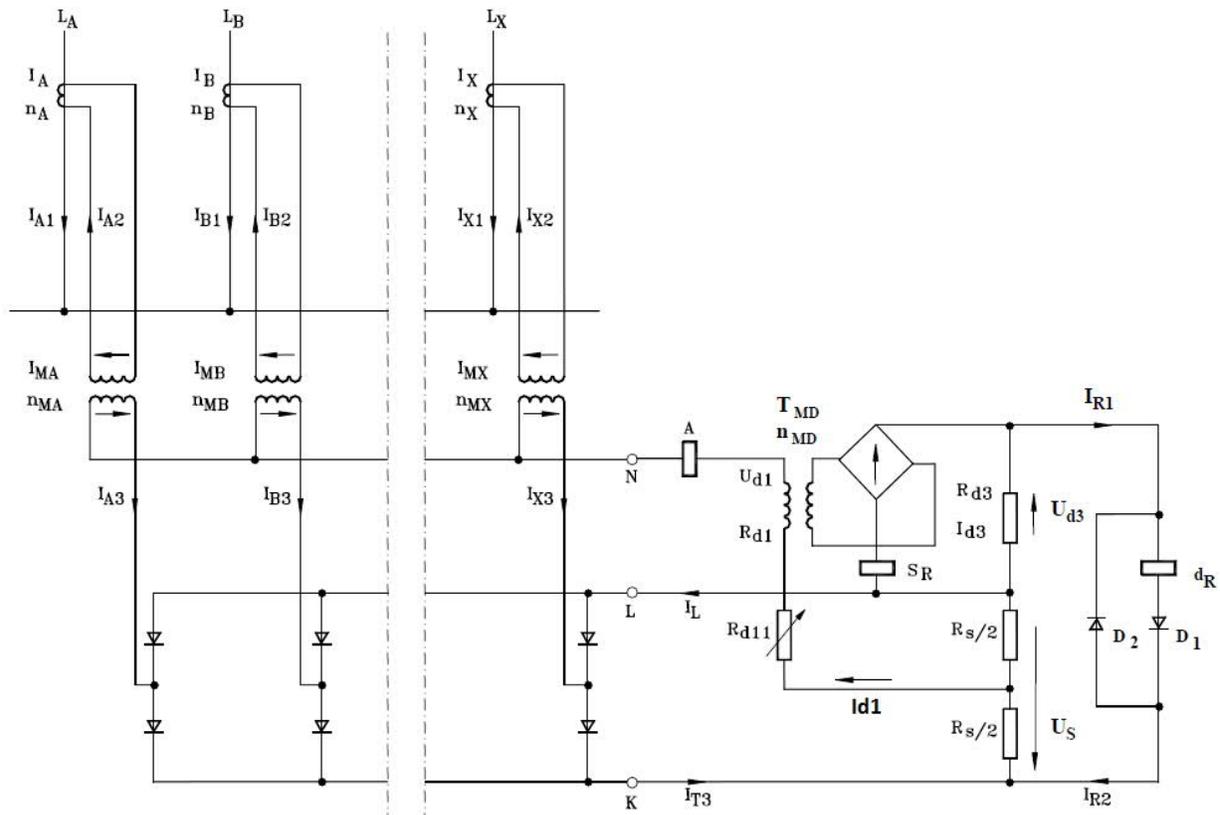


Figure 1: Principal schematic of the analog percentage restrained differential protection [2]

Stability of this protection relay is guaranteed, regardless the primary fault current level and CT saturation if the total CT secondary circuit loop resistance, transferred across its auxiliary current transformer to the relay side, is less than or equal to the resistance  $R_{d11}$  in the differential relay branch (for operating slope of 0.5). Due to this special design feature, the relay allows much bigger resistance to be included in the secondary circuits of the individual main current transformers than in the original high impedance scheme. It can accommodate the different CT ratios by use of auxiliary current transformers. The CT requirements are very moderate and the relay can tolerate other relays on the same CT core. At the same time, by the use of high-speed reed relays, this bus differential protection scheme reliably detects internal faults within 1 to 3 milliseconds and issues the trip signal to the high voltage circuit breakers within 9 to 13 milliseconds from the occurrence of the internal fault.

#### Numerical differential protection

In numerical busbar protection relays, all CT and VT inputs are galvanically separated from each other. All analog input quantities are sampled with a constant sampling rate and

these discrete values are then transferred to corresponding numerical values (i.e. AD conversion). After this conversion, only the numbers are used in the protection algorithms. Therefore it is impossible to directly re-use and copy the operating principles from the analog bus differential schemes described above, because there is not any galvanic connection between the CTs.

Therefore, if the secondary circuit resistance is not any more very important, what then are the crucial factors for the numerical relay design [8] in order to guarantee the stability of the protection algorithm?

Actually it is the time available to the differential relay to make the measurements during CT saturation and to take the necessary corrective actions. This practically means that the relay has to be able to make the measurement and the decision during the short period of time, within each power system cycle, when the CTs are not saturated. As described in the references [2] and [3] this time, even under extremely heavy CT saturation, is for practical CT around 2ms. Therefore, it was decided to take this time as the design criterion for the

minimum acceptable time before saturation of a practical magnetic CT cores.

However, if the necessary preventive action has to be taken for every single HV bay connected to the protection zone, the relay algorithm would be quite complex. Therefore, it was decided to try to re-use the important quantities from the analog percentage restrained differential protection relay, like incoming, outgoing and differential currents, within the numerical design. These three quantities can be easily calculated numerically from the raw sample values from all analog CT inputs connected to the differential zone. At the same time, they have extremely valuable physical meaning, which clearly describes the condition of the protected zone during all operating conditions.

By using the properties of only these three quantities, a differential algorithm has been formed which is completely stable for all external faults and very fast for the internal faults. This differential algorithm is already proven in several thousands of installations all over the world. All problems caused by the nonlinearity of the CTs are solved in an innovative numerical way on the basic principles described above. Detailed description of this algorithm is available in reference [8].

### III DYNAMIC ZONE SELECTION FOR COMPLEX STATION LAYOUTS

Efficient dynamic zone selection, referred also sometimes in the relay literature as busbar replica, is a key function for complex busbar arrangements where one bay can be dynamically associated with several differential protection zones. In such installations CT connections towards the protection zones will vary over time. Therefore it is important that CT connections towards the protection zones are properly selected. Many methods have been developed to provide advanced dynamic zone selection to cope with the increased complexity and flexibility. For example graphical representation of busbar topology, zone selection based on graph theory, etc. where proposed. New simple and computationally efficient alternative has been proposed in [9] and implemented in latest generation of numerical busbar protection [10].

Main features of the new implemented algorithm are:

1. Applicable for up to six freely configurable differential protection zones and up to twenty-four freely configurable CTs.

2. Applicable for single, double and triple busbar arrangements with or without transfer bus.
3. Applicable for double circuit breaker or one-and-half circuit breaker stations.
4. Easy incorporation of bus-section and/or bus-coupler bays (that is, tie-breakers) with one or two sets of main CTs.
5. Easy incorporation of bus-sectionalizing disconnectors.
6. Easy scheme engineering including even the future bays.

The integrated zone selection component requires information of several different types at different levels:

1. The static configuration information. It concerns, for instance, the type and operation mode of each bay, the maximum number of used protection zones, etc.
2. Dynamic data which affects the interconnection of bus zones dynamically. It concerns the operational status of the disconnectors located at each individual bay and bus sectionalizing disconnectors, together with operational status of bays (e.g. bay out of service).

The integrated zone selection component ensures the dynamical adaptability to most common busbar configurations by:

1. Accurate dynamic linking of measured bay CT currents to appropriate differential protection zones.
2. Selective routing of busbar differential protection zones trip commands to only the circuit breakers connected to the faulty zone.
3. Selective tripping for circuit breaker failure protection by correct marshaling of backup-trip commands from internally integrated or externally located circuit breaker failure protections to all surrounding circuit breakers.
4. Efficient zone interconnection (i.e. load-transfer), which in principle is a merging of the two or more differential zones when required by substation actual topology.
5. Easy handling of bus-sectionalizing disconnectors.
6. Disconnector and/or circuit breaker status supervision and alarming.

In addition, so-called parallel connection, which occurs at a bus-section bay or a bus-coupler bay when both of its ends are assigned to the same protection zone is also easily handled in new design. The zone selection algorithm then ensures that both currents from a bus-section bay or a bus-coupler bay are

taken out from the respective zone(s) of the differential protection. In addition, there is possibility for the end user to determine by a setting if a tripping is allowed for the bus-section or bus-coupler circuit breaker while there is a parallel connection in progress.

#### IV RTDS TEST SETUP

Real Time Digital Simulator, RTDS was used to create and run the test cases for new busbar protection (i.e. BBP) with six differential zones and new Zone Selection [10]. The used network topologies and test cases are included in coming sections of this document.

RTDS is a Real Time Digital Simulator which has the capability of simulating the power system in real time. Real time means that we can operate a breaker, force a fault, or make any change in the power system and evaluate BBP behavior for the same disturbance in real time. This is possible

due to several processing units that are utilized in parallel which give the RTDS a high computational power. The calculations are done in every time step, with typical step value lying between  $50\mu s$  and  $120\mu s$ . Testing is performed in two parts: functional and dynamic.

Functional tests are intended to verify the ability of busbar protection function to clear all internal faults with absolute selectivity. Faults are simulated under different switchgear configurations and at different location. The protection function has behaved correctly during all tests cases.

Substation switchgear arrangement used to run functional test cases is shown in Figure 3.

The dynamic tests are performed to evaluate BBP behavior during different transient processes (e.g. CT saturation).

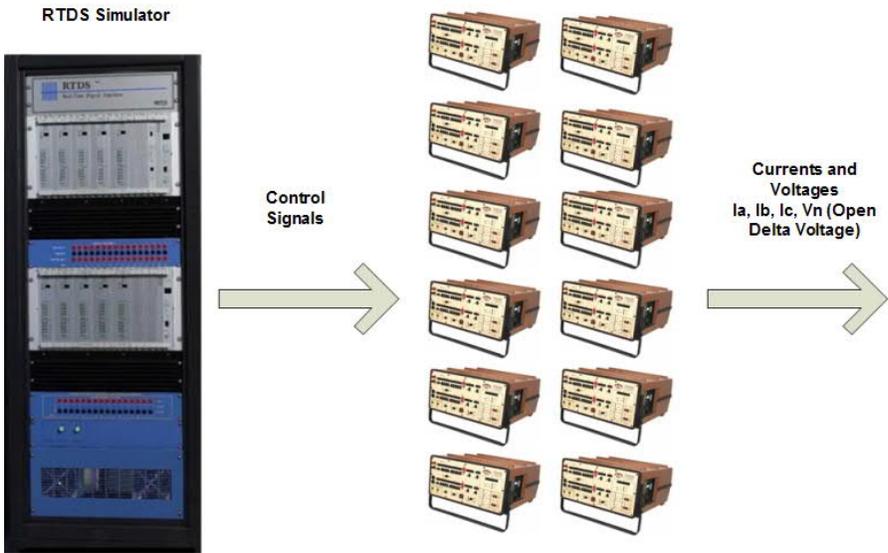


Figure 2: RTDS setup

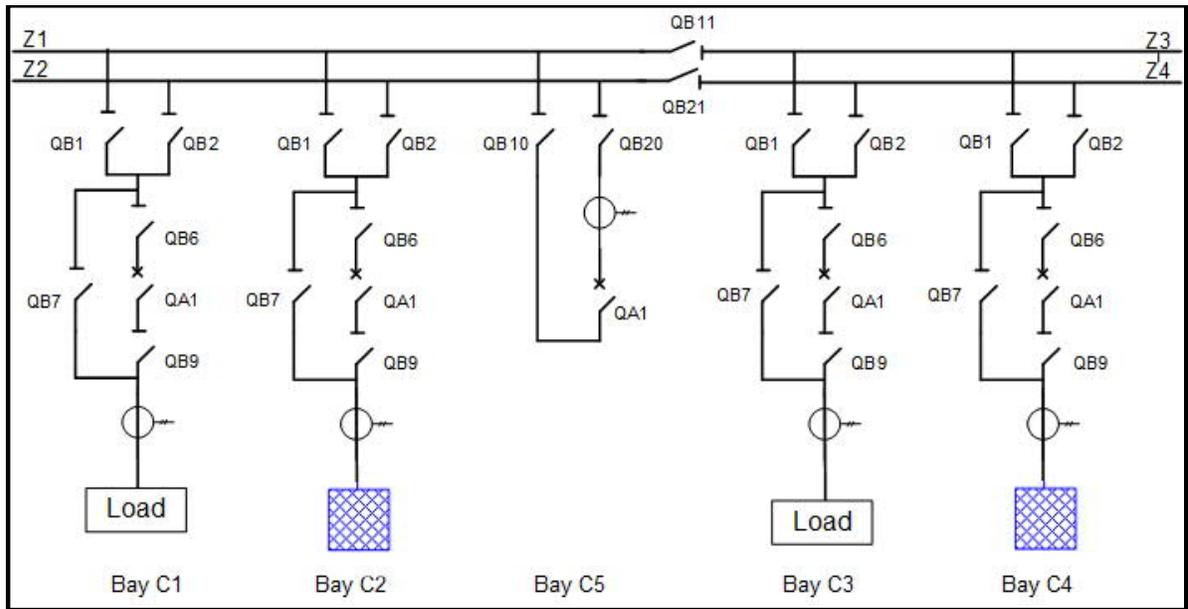


Figure 3: Network model used for functional testing of busbar protection

### Overall Test Scope

The test objectives are:

1. To validate the security of busbar protection scheme during external faults associated with CT saturation
2. To validate the dependability of busbar protection scheme to detect and to isolate internal faults with absolute selectivity.
3. To validate the ability of busbar protection scheme to correctly distinguish and isolate special fault types such as evolving fault, while remaining stable during auto-reclosing cycle on a OHL for external permanent fault.
4. To validate busbar protection scheme performance concerning the busbar replica in steady-state condition and during configuration changes.
5. To validate the performance of open CT detection supervision to prevent mal-operation of busbar protection function during CT secondary circuit failure.
6. To validate the performance of breaker failure and end fault protection functions.
7. To validate the performance for both 50Hz and 60Hz power system.

### Simplified description of RTDS dynamic test cases.

1. Symmetrical and asymmetrical faults have been tested with primary time constants 100, 200, and 350ms and fault inception angle  $0^\circ$  (maximum DC offset),  $30^\circ$ ,  $60^\circ$ ,  $90^\circ$ ,  $120^\circ$  and  $150^\circ$  degree. Internal and external faults were performed with different combinations of main current transformer ratios and different remanence levels.

2. Test cases for heavy saturation of the current transformer associated with the faulted zone. Remanence level of up to 75% have been tested in one CT while all other CTs were kept saturation free.

3. Evolving faults, simultaneous faults and effect of auto-reclosing have been also tested. The effects of auto-reclosing were tested in order to prove the stability of the protection when exposed to AR during re-closing onto external permanent faults.

4. Internal and external faults were tested in conjunction with busbar replica faulty status.

5. End fault and breaker failure protection were tested and the function performance was verified.

## V RESULTS FROM RTDS FUNCTIONAL TESTING

These tests are performed in order to verify the features which operates relatively slow (e.g. in order of seconds) within the tested BBP.

### Test cases for selective operation of the BBP

Table 1 includes the tested scenarios and test results for selective BBP operation when the Zone Selection receives completely correct information about the status of all primary apparatuses involved in the BBP scheme.

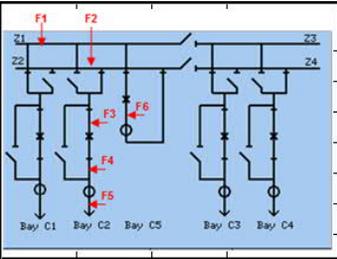
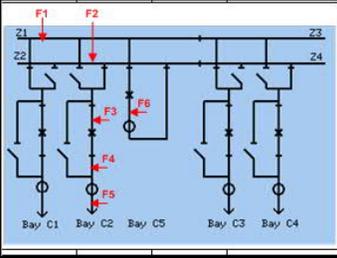
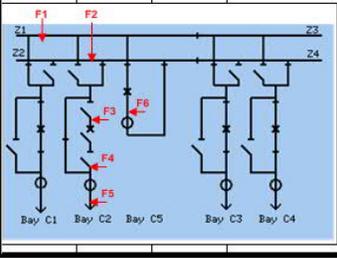
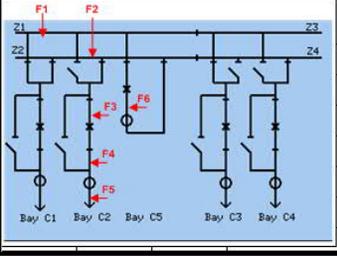
	Fault Location	Bay C1 Trip	Bay C2 Trip	Bay C3 Trip	Bay C4 Trip	Bay C5 Trip	Zone 1 Trip	Zone 2 Trip	Zone 3 Trip	Zone 4 Trip	Results
F1	✓	–	–	–	–	✓	✓	–	–	–	ok
F2	–	✓	–	–	–	✓	–	✓	–	–	ok
F3	–	✓	–	–	–	✓	–	✓	–	–	ok
F4	–	✓	–	–	–	✓	–	✓	–	–	ok
F5	–	–	–	–	–	–	–	–	–	–	ok
F6	✓	✓**	–	–	–	✓	✓	✓**	–	–	ok
**Back up trip due to permanent fault between CT and bus coupler CT. Tripping after set value for tZeroCurrent											
	Fault Location	Bay C1 Trip	Bay C2 Trip	Bay C3 Trip	Bay C4 Trip	Bay C5 Trip	Zone 1 Trip	Zone 2 Trip	Zone 3 Trip	Zone 4 Trip	Results
F1	✓	–	✓	–	–	✓	✓	–	–	–	ok
F2	–	✓	–	–	✓	✓	–	✓	–	–	ok
F3	–	✓	–	–	✓	✓	–	✓	–	–	ok
F4	–	✓	–	–	✓	✓	–	✓	–	–	ok
F5	–	–	–	–	–	–	–	–	–	–	ok
F6	✓	✓**	✓	–	✓**	✓	✓	✓**	–	–	ok
**Back up trip due to permanent fault between CT and bus coupler CT. Tripping after set value for tZeroCurrent											
	Fault Location	Bay C1 Trip	Bay C2 Trip	Bay C3 Trip	Bay C4 Trip	Bay C5 Trip	Zone 1 Trip	Zone 2 Trip	Zone 3 Trip	Zone 4 Trip	Results
F1	✓	–	✓	–	–	✓	✓	–	–	–	ok
F2	–	✓	–	–	✓	✓	–	✓	–	–	ok
F3	–	–	–	–	–	–	–	–	–	–	ok
F4	–	✓	–	–	✓	✓	–	✓	–	–	ok
F5	–	–	–	–	–	–	–	–	–	–	ok
F6	✓	✓**	✓	–	✓**	✓	✓	✓**	–	–	ok
**Back up trip due to permanent fault between CT and bus coupler CT. Tripping after set value for tZeroCurrent											
	Fault Location	Bay C1 Trip	Bay C2 Trip	Bay C3 Trip	Bay C4 Trip	Bay C5 Trip	Zone 1 Trip	Zone 2 Trip	Zone 3 Trip	Zone 4 Trip	Results
F1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	ok
F2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	ok
F3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	ok
F4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	ok
F5	–	–	–	–	–	–	–	–	–	–	ok
F6	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	ok
** During load transfer all measuring zones are merged into one zone.											

Table 1: Summary of test results for Selective Operation of BBP

Primary equipment		Status in busbar protection		Alarm facility	
Normally Open auxiliary contact status ("closed" or "a" contact)	Normally Closed auxiliary contact status ("open" or "b" contact)	Scheme 1 RADSS	Scheme 2 INX	Alarm after settable time delay	Information visible on local HMI
open	open	closed	Last saved position	yes	intermediate_00
open	closed	open	open	no	open
closed	open	closed	closed	no	closed
closed	closed	closed	closed	yes	badState_11

Table 2: Overview of INX and RADSS schemes used for Zone Selection

Test cases with incorrect information into zone selection logic

Information about the topology of the protected station is mandatory for the proper assignment of current transformer to the respective protection zones and selective clearance during faults. The tested BBP offers two different operating principles to deduce the position of a primary apparatus (i.e. either disconnect or circuit breaker) in case when status of two auxiliary contacts is lost. Treatment of primary apparatus auxiliary contact status for the two principles available within the tested BBP is shown in Table 2.

#### Remarks on incorrect bus replica test results

As seen from Table 2 above, the difference between the two schemes used for bus replica is only how an intermediate position (i.e. "00") of any primary apparatus has been interpreted.

RADSS scheme works on the principle if not open then closed, while INX scheme uses the last saved valid position.

From the application point of view RADSS scheme maintain security and lacks selectivity, as all the object with intermediate position is treated as closed, which typically results in zone merging.

On the other hand, INX scheme maintain selectivity and lacks security under specific circumstances when the position of the primary apparatus does not represent the actual position anymore. Hence, INX scheme requires that while the switchgear alarm signal is active, it shall not be permitted to operate any other isolator or circuit-breaker in the station. As the isolators require a certain time to operated, alarm related to the position is time delayed.

The performance of the protection scheme during persisted bus image alarm is decided by the user during the engineering of the BBP scheme. If desired, the affected zone can be blocked while the switchgear alarm is active. Table 3 includes overview of the test results when incorrect apparatus status is given to BBP.

#### Testing of Open CT detection

Current transformer secondary circuit supervision represents an essential part of the busbar protection scheme. The supervision guarantee the stability during open or short-circuited main CT secondary circuits.

The tested BBP [10] includes two techniques for CT secondary circuit supervision:

1. Fast operating open CT detection logic.
2. Slow operating open CT detection logic.

Fast operating open CT detection logic detects instantly the moment when a healthy CT secondary circuit carrying the load current is accidentally opened. This logic can only detect open CT condition when an already connected CT with secondary load current being open circuited. This logic is designed for instant blocking of the affected busbar protection zone(s). Blocking is zone and phase selective even if the false differential current is higher than the set value for trip level.

Slow operating open CT detection logic will detect most abnormalities in the CT secondary circuits or in the dynamic zone selection logic. However, this logic has an intentional time delay.

#### Remarks on open CT detection test results

Fast open CT detection is a unique feature for the tested BBP. The logic is based on monitoring the changes in the three current quantities used in the measuring algorithm of the differential protection [8]. It is fully capable to distinguish between open CT conditions and real disturbance in the power system. The logic has as well security measures in order to secure correct operation of the protection feature during internal fault conditions. The logic is designed only to detect failure of healthy CT secondary circuit carrying the load current and block selectively the affected zone and phase. However, the Fast OCT detection does not operate, for example, for situation when a new bay is connected to the differential zone with its CT secondary circuits being open/short circuited.

Slow OCT is based exclusively on monitoring the presence of the differential current and hence, it will detect all abnormalities in the CT secondary circuit and must be always applied. As differential current also exist during internal busbar fault, the logic cannot distinguish between open CT conditions and real internal fault and hence it must be time delayed in order to prevent possible blocking during internal fault. From the application point of view, using both fast and slow open CT at the same time enhances the overall BBP scheme performance.

Fault Location	Bay C1	Bay C2	Bay C3	Bay C4	Bay C5	Zone 1	Zone 2	Zone 3	Zone 4	Results
	Trip									
F1	✓	✓	✓	✓	✓	✓	✓	✓	✓	ok
F2	✓	✓	✓	✓	✓	✓	✓	✓	✓	ok
F3	✓	✓	✓	✓	✓	✓	✓	✓	✓	ok
F4	✓	✓	✓	✓	✓	✓	✓	✓	✓	ok
F5	—	—	—	—	—	—	—	—	—	ok
F6	✓	✓	✓	✓	✓	✓	✓	✓	✓	ok

_protection/SwitchgearStatus(87B)/BDCGRPC(87B)2/Outputs INSTNAME Bay C1_QB2 Beh On POSITION intermediate_00 CLOSED 1 OPEN 0 ALARM 1		Initial condition : Bay C1_QB2 Open. Test condition : Intermediate position (0,0) Set value applied : Scheme 1_RADSS. Test result: The position is treated as closed resulting in zone merg
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Fault Location	Bay C1	Bay C2	Bay C3	Bay C4	Bay C5	Zone 1	Zone 2	Zone 3	Zone 4	Results
	Trip									
F1	✓	—	—	—	—	✓	—	—	—	ok
F2	—	✓	—	—	✓	—	✓	—	—	ok
F3	—	✓	—	✓	✓	—	✓	—	—	ok
F4	—	✓	—	✓	✓	—	✓	—	—	ok
F5	—	—	—	—	—	—	—	—	—	ok
F6	✓	✓**	✓	✓**	✓	✓	✓**	—	—	ok

_protection/SwitchgearStatus(87B)/BDCGRPC(87B)2/Outputs INSTNAME Bay C1_QB2 Beh On POSITION intermediate_00 CLOSED 0 OPEN 1 ALARM 1		Initial condition : Bay C1_QB2 Open. Test condition : Intermediate position (0,0) Set value applied : Scheme 2_INX Test result: The last position saved is used and the isolating switch is still treated as open
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Table 3: Summary of test results for fault cases with incorrect bus replica

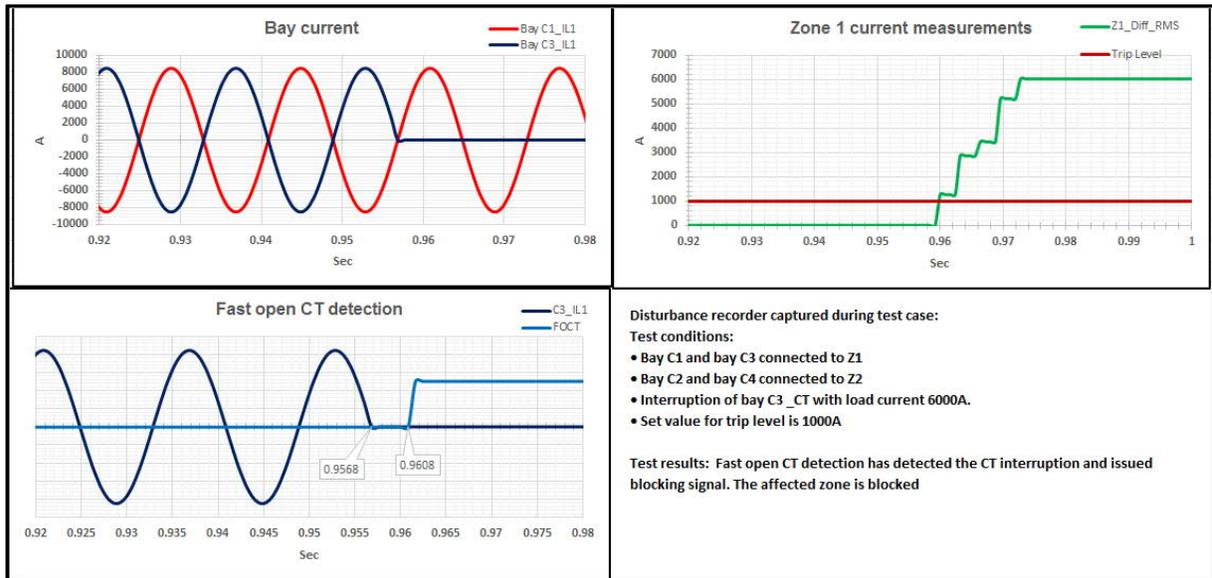


Figure 4: Test results for fast open CT detection logic with load current higher than the trip level

Figure 4 depicts the test results for Fast CT open secondary circuit supervision.

## VI RESULTS FROM RTDS DYNAMIC TESTING

The dynamic tests are used to verify BBP features which operates very fast (e.g. in order of milliseconds).

### External fault test cases

Stability of busbar protection scheme during external faults and in particular when the CT start to saturate due to high fault current or accumulated remanence is the most critical factor when assessing the security of busbar protection scheme.

Despite low CT requirement for tested BBP, the algorithm and stabilization feature used make it largely insensitive to CT saturation phenomena. Test results has indicated that busbar protection has remained stable for all test cases of external faults including cases where the CT of the faulted bay has saturated within 2ms.

Test cases for external fault are based on the RTDS network model presented in Figure 5.

For all simulated cases, CT1 and CT2 were kept practically saturation free while the magnetizing characteristics for CT3 has been controlled by varying the transient dimensioning factor KTF between 0.5 and 2. Test cases with KTF=0.5 represents the relay performance on the limit of defined CT requirements in the BBP manual.

### Summary of test results for external fault

Fault cases for single phase and multi-phase were simulated with DC time constant up to 350ms and inception angles 0°, 30°, 60°, 90°, 120° and 150°. All CTs were kept saturation free with exception of CT3 where for all fault cases, additional remanence of 75% was used even at a reduced transient dimensioning over sizing factor (KTF) of 0.5. The protection function behaved correctly and has remained stable during all external fault cases.

Figure 6 depicts the performance of the BBP for test case with KTF=0.5 and remanence of 75%. Note that fastest CT saturation is actually achieved for pure AC primary current waveform (i.e. without any DC component) as shown in this figure.

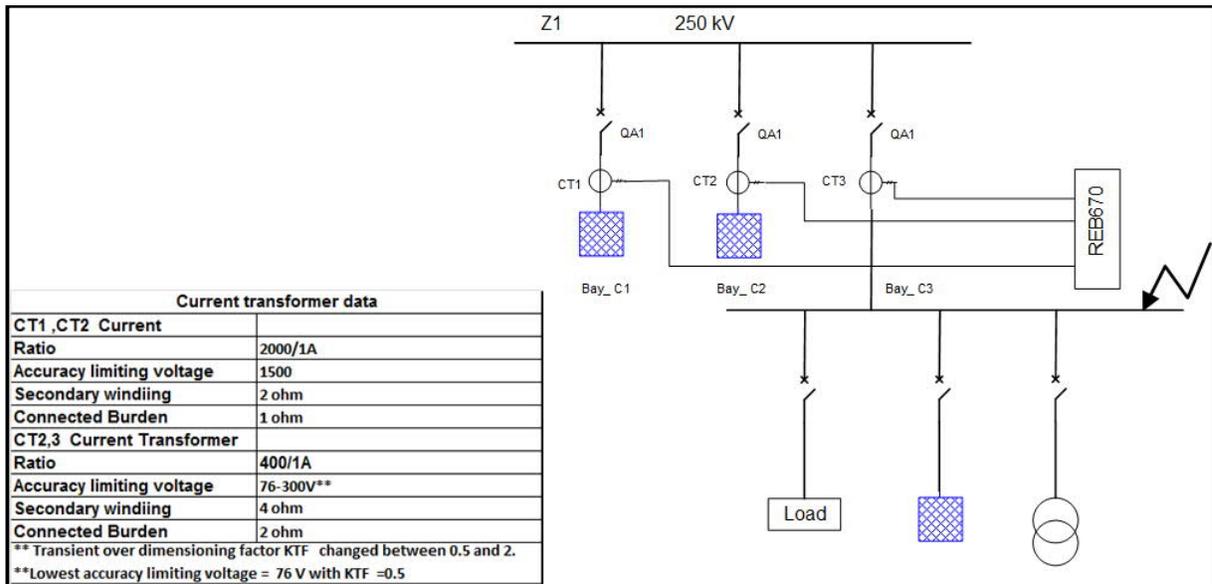


Figure 5: Network model used for the testing external fault with CT saturation

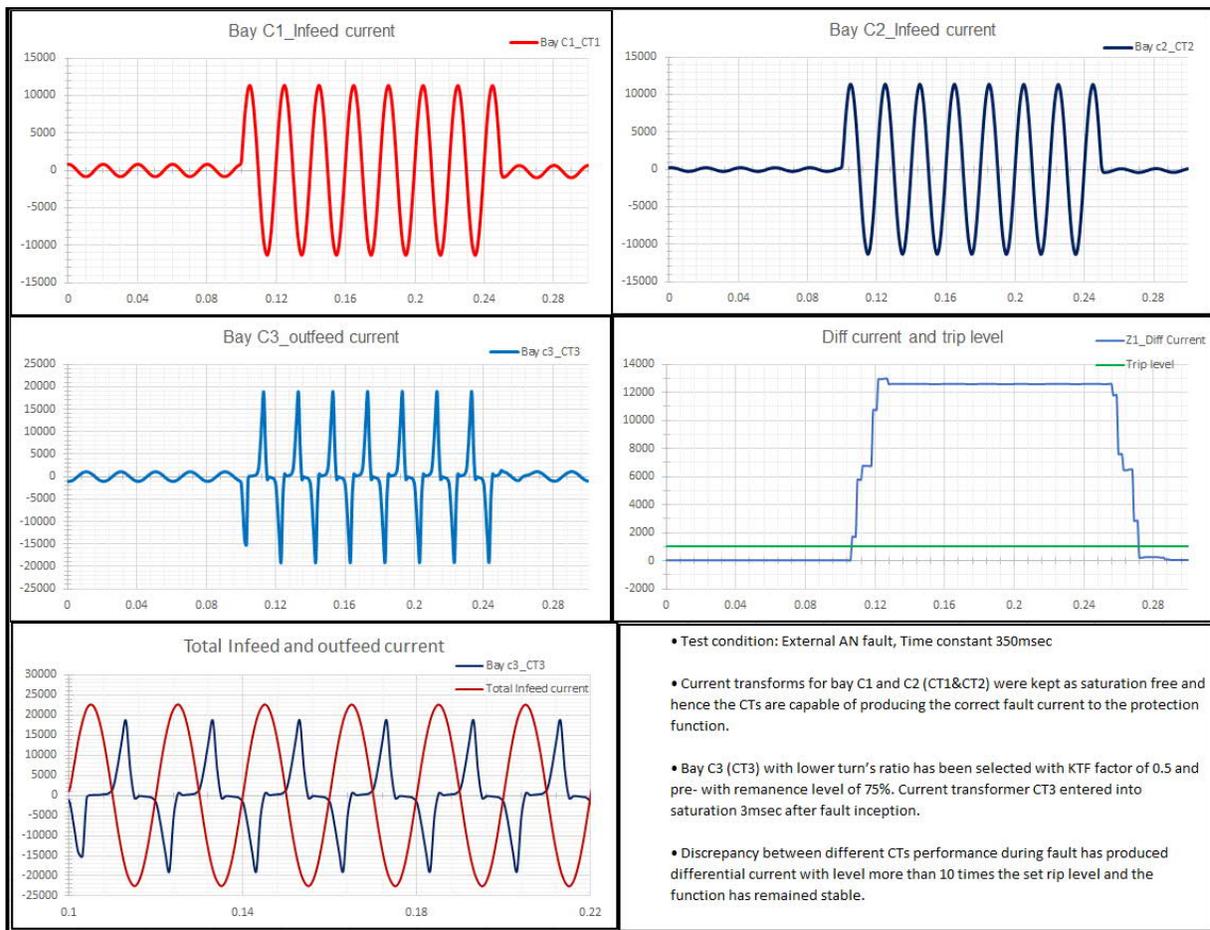


Figure 6: Test case for external fault with the faulted bay CT exposed to severe saturation

#### Remarks on the test results for external fault

Current transformer saturation causes busbar protection schemes to measure false differential current that do not exist in the power system and special steps must be in place in the algorithm in order to prevent mal-operation.

All low impedance busbar protection schemes are based on percentage-restrained differential characteristic where the trip level is automatically somewhat increased based on the amount of current that flows through the bus. This restrain principle only handles moderate CT saturation and hence all busbar protection relays must have an additional measure in order to handle cases where heavy CT saturation may produce differential current tens of times higher than the set trip level. Pay attention that for the tested BBP the slope of the operating characteristic is fixed to 0.53 in the algorithm!

The tested BBP [10] has a special CT saturation algorithm [8] that looks for the properties of incoming, outgoing and differential current in order to cope with CT saturation of any main CT connected to the protection zone. This algorithm guarantee the stability during external faults and do not affect the performance of the protection function during internal faults.

#### Evolving and simultaneous fault test cases

Bus protection scheme performance during evolving and simultaneous fault conditions plays an important role when assessing the security and dependability of busbar protection scheme.

Security aspects refers to the ability of the protection function to remain stable during clearing / switch onto external faults and dependability aspect refers to the ability of

the protection function to detect and operate for all internal faults even including the faults which may evolve from external to internal.

1. Evolving faults from external to internal with evolving time 5, 10, 15, 20ms.
2. Evolving faults from internal to external with evolving time 5, 10, 15, 20ms.

Summary for fault cases and test results for evolving fault

Following are the test cases included in the test scope:

The protection function has behaved correctly in all test cases. Figure 7 shows the performance of the tested BBP during test case for evolving fault from L1 external to L2 internal.

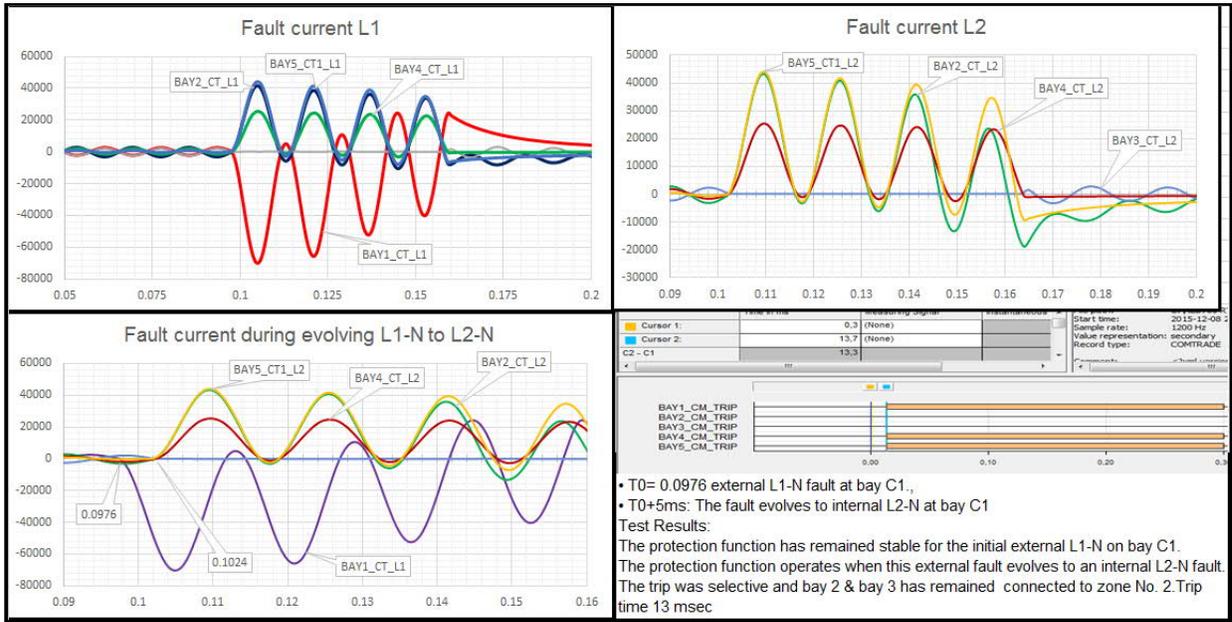


Figure 7: BBP performance for evolving fault

### Internal fault test cases

The performance requirements for busbar protection scheme during internal faults are speed and selectivity. Current transformer saturation during internal faults typically shall not influence the proper operation of the BBP. The result of current transformer saturation during internal fault is a loss of infeed from the bay where the CT has saturated and consequently lower measured value of the differential current. However, the principle applied on how to set the trip level for busbar protection scheme takes care of this situation as the trip level has to be set around 50% of the absolute minimum expected fault level.

Figure 8 depicts the performance of tested BBP during internal fault with the current transformer saturation.

### Functional tests for circuit breaker failure protection

Circuit breaker failure protection can be current based, circuit breaker position based, or an adaptive combination of these two conditions. Current check with extremely short reset time is used as check criterion to achieve high security against unnecessary operation. Contact check criteria can be used where the fault current through the breaker is small.

The dependency of breaker failure function on busbar protection is only to utilize the bus replica available for bus protection function to inter-trip busbar zone when required. Figure 9 depicts breaker failure test case.

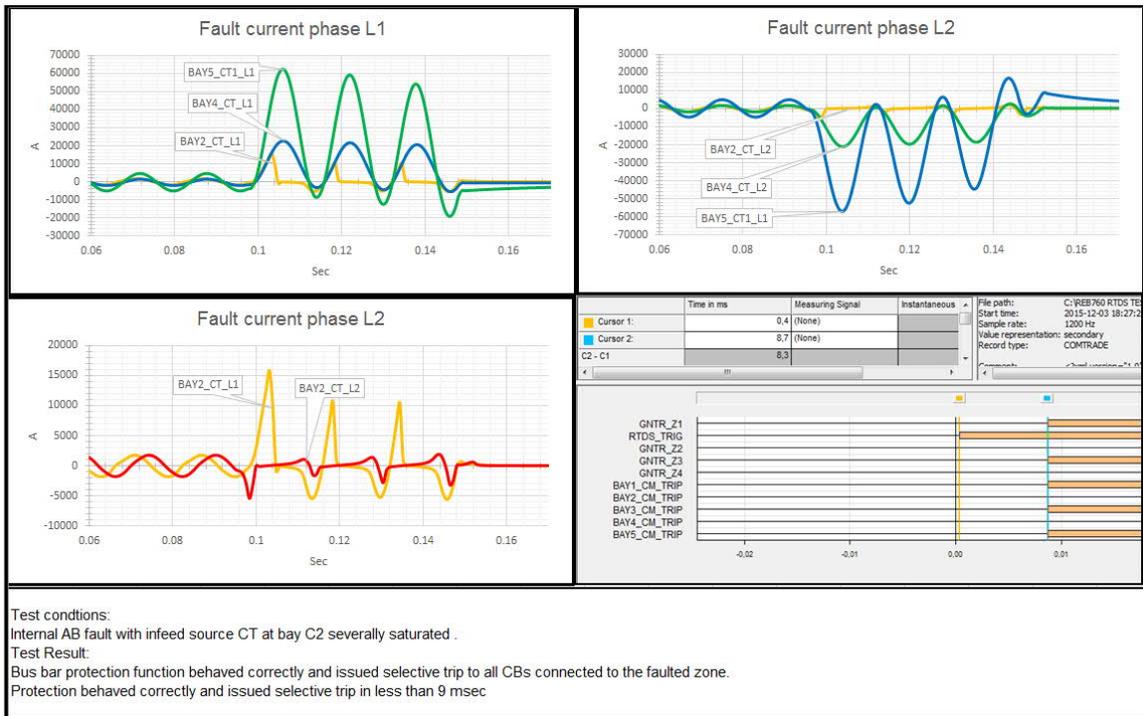


Figure 8: Protection function performance for internal fault with CT saturation

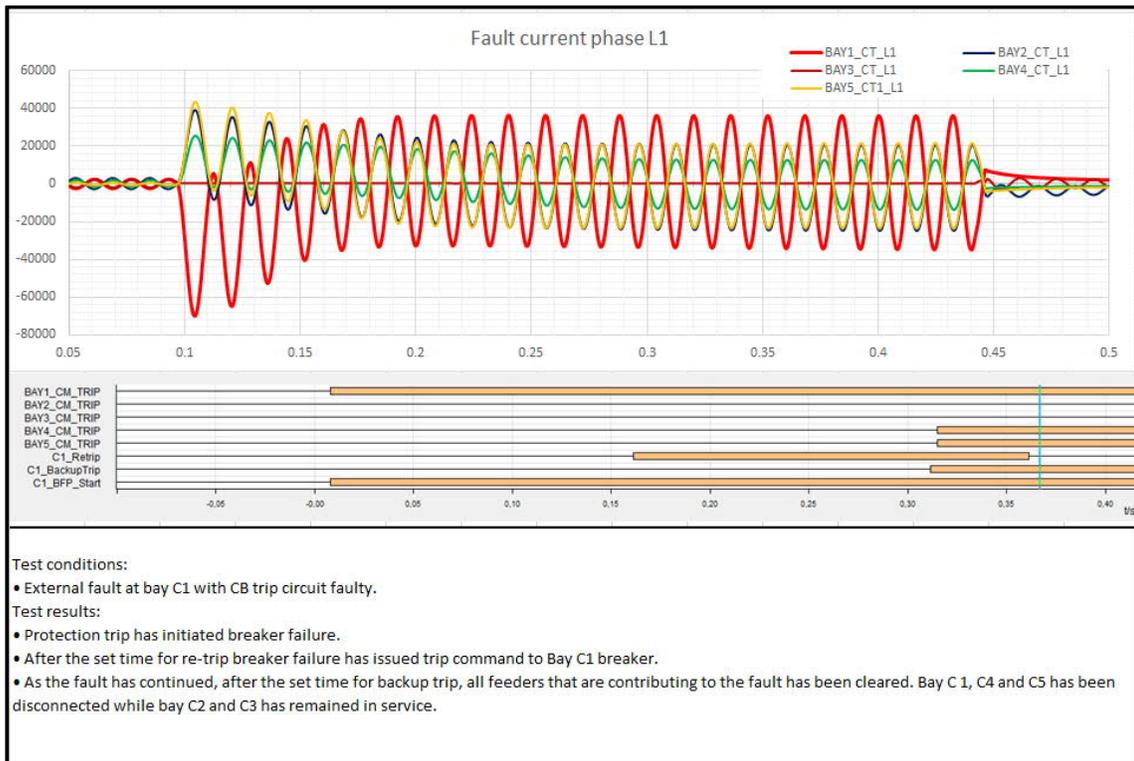


Figure 9: Test results for breaker failure protection

## VII OPERATION EXPERIENCE IN THE FIELD

The used differential protection algorithm, which is presented in more details in reference [8], has been applied for more than ten years in several thousands of BBP installations all around the world. Many operations for actual internal faults have been recorded and some of them will be presented in this section.

### Internal three-phase fault in 110kV GIS Station

In an 110kV GIS substations a new bay was supposed to be added while rest of station was kept in service. By accident, one of the workers in the station has succeeded to close a bus earthing switch on a live part of the 110kV GIS. As a result 35kA, three-phase, internal busbar fault has occurred inside 110kV GIS switchgear. Due to extremely fast trip from the

BBP the total fault duration, including CB operating time, was only 45ms. As a result the GIS did not rupture and the personnel working around the faulty GIS was not hurt at all. Only minimal damages to the GIS switchgear has been encountered. The recorded three phase-to-ground voltages in a neighboring 110kV substation during this fault are shown in Figure 10. The voltages are given in secondary volts in that figure. From this figure is clearly visible that the fault was disconnected extremely quickly.

### Internal L2-to-Gnd fault in 400kV GIS Station

An internal L2-Gnd fault has been recorded in a 400kV substation. A disconnector arm got broken during movement touching ground within a GIS switchgear. As a result 45kA fault current appeared in phase L2. The BBP operated within 7ms as shown in Figure 11.

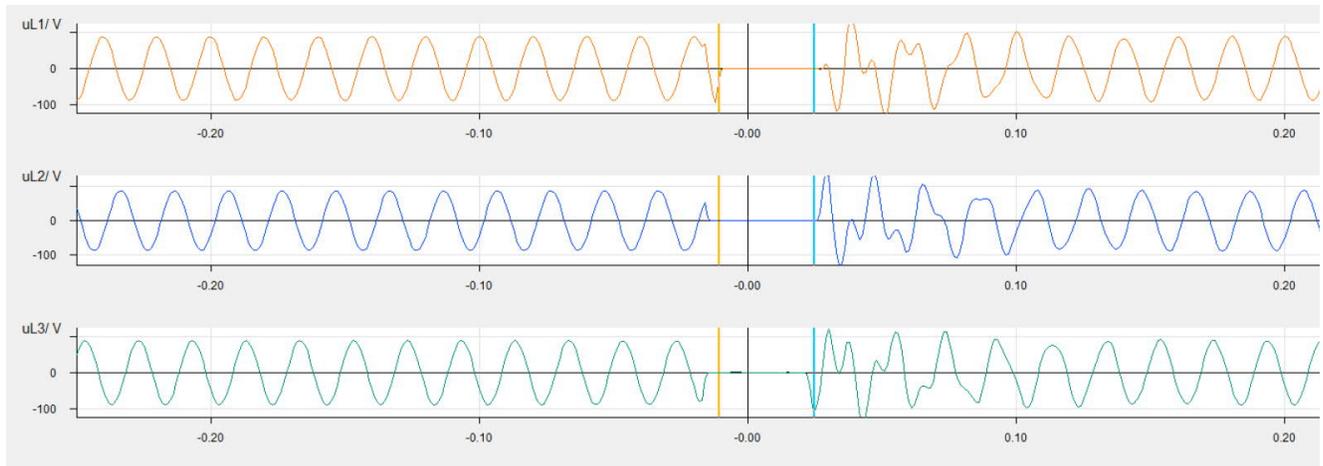


Figure 10: Voltages in 110kV network during three-phase busbar fault

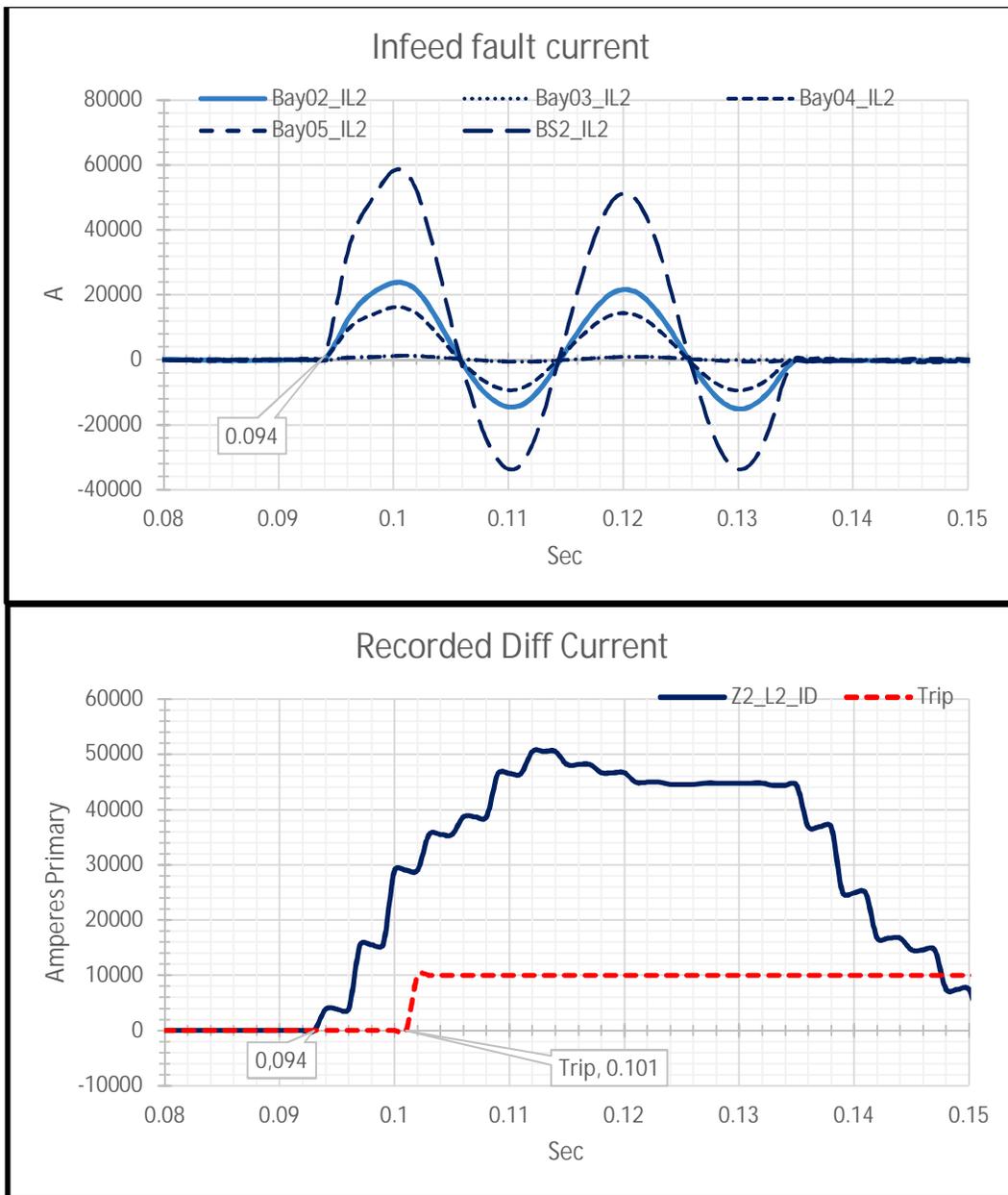


Figure 11: Tripping for L2-Gnd fault on a 400kV Bus

### VIII CONCLUSION

It has been shown that numerical busbar differential protection relay [10] has the same performance as one of the best analog busbar differential relays [2] ever produced. Additionally it offers many advantages given by numerical technology such as up to six differential protection zones, software based zone selection, simple scheme engineering,

disturbance and event recording, built-in CB failure protection, IEC61850 communication, etc.

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## X AUTHORS

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Zoran is a Senior Application Engineer at ABB AB, Grid Automation Products in Vasteras, Sweden. He received his MSEE degree with honors from the University of Belgrade, Serbia in 1990 and PhD degree in electrical engineering from Lund University, Sweden in 2008. Since 1993 he has been working in the area of power system protection and control within ABB Group of companies, where he had various engineering positions. From 2008 to 2015 he was ABB Global Product Manager for Generator and Transformer Protection. He has published many technical papers in the relay protection area and holds more than fifteen patents. Zoran has participated in different CIGRE, IEC and PSRC/IEEE working groups and was the Convener for CIGRE Working Group "Modern techniques for Protecting Busbars in HV Networks". In 2014 he received Technical Committee Award from Cigré Study Committee B5 (Protection and Automation). Zoran likes playing chess and when time allows, he participates in chess tournaments and Swedish chess league competition.

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Mike joined ABB Inc. in Raleigh, North Carolina as a Senior Applications / Product Specialist in November 2011. Prior to relocating to North America, Mike worked as a Senior Applications Specialist / Senior Regional Technical Manager for 12 years at the SA Product factory in Västerås, Sweden. Before joining ABB AB in Sweden in January 2000, Mike was Senior Consultant, Protection (Transmission) at Eskom (national power utility, South Africa). Mike joined Eskom as a training engineer in 1983, and rose to Protection Design Manager (Line Protection), before switching to Senior Consultant. Mike graduated from the University of Cape Town with BSc (electrical engineering) degree (with honors) in 1980.