Process Bus for Bus Differential – Challenges, Solutions, and Opportunities

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ABSTRACT

The use of process bus and Non Conventional Instrument Transformers (NCIT) are a logical step in improved bus protection. Different bus protection principles will see different levels of process bus penetration. High impedance bus differential protection may still be used in many applications however this principle will not be impacted by process bus technology due to the operating characteristics.
All types of low impedance bus differential protection will benefit from process bus technology. The paper discusses how the use of merging units will close the gap between centralized busbar protection and distributed busbar protection. The concept of merging unit as a function instead of a physical device enables numerous different solutions. A merging unit can be designed as a plain device; only feeding the bus differential protection with sampled measured values, or it can be implemented with a feeder or line protection relay where the main function is to protect the incoming or outgoing line or feeder as well as delivering the sampled measured value to the busbar protection. This concept is used to save in device count, wiring and engineering work.
Process bus technology enables the possibility to use NCIT. This technology has great advantages such as higher accuracy and fewer problems with CT-saturation. There are also constraints which should be considered, and these are discussed. Based on the transient requirements given in related standards, recommendations are given for the use of NCIT for bus differential protection.
Finally, different communication topologies for bus differential protection are reviewed and checked against the current standards. Recommendations for the future standardization are given to improve the reliability and security of bus differential protection using process bus technology.

I. INTRODUCTION

Busbars are used to connect electrical elements like generators, transformers, lines or feeders in a switchyard or switchgear. There are a lot of different types of busbars used in our industry [1].
In any case busbars are important parts of the power system. Electrical faults on busbars often occur with high short circuit currents. Due to this a fast fault clearing time is required to maintain the stability of the power system. On the other hand the busbar protection need to be stable in case of external faults because losing a busbar has severe impact to the power system.
Today different types of busbar protection schemes are in use. The most common scheme for a high level of performance is the bus differential scheme which exists in the following categories:

- Differentially connected overcurrent
- Partial differential overcurrent
- High-impedance differential
- Low-impedance differential

All kinds of bus differential protection are based on Kirchhoff's current law. This law states that the sum of all currents flowing in and out of a protected zone is zero as long as there is no fault inside the protected zone:

$$\sum_{k=1}^{n} I_k = 0 \qquad (1)$$

k: consecutive number of bay / feeder
n: total number of bays / feeders

As shown in Figure 1 the protected zone of bus differential protection is defined by the location of the current transformer. Based on this a high selectivity is reached and no additional time delay is needed. This guaranties a high speed of bus differential protection.

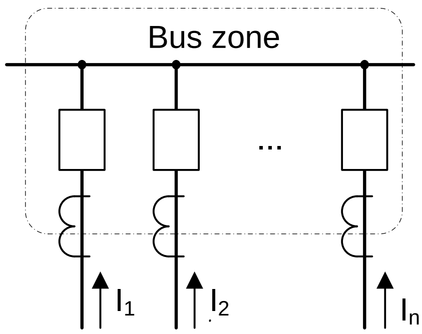

Figure 1: Single line diagram of a busbar with n feeders

The availability and the characteristic of the current transformer at the protected zone have a major impact on the selection of the busbar protection scheme.

If CT's are not available for all bus elements partial differential overcurrent can be used. If all bus elements are monitored by CT's, bus differential protection may be applied.

	Selectivity	Speed	Sensitivity	Security	CT-Require-ments
Partial differential overcurrent	-	-	-	-	+
Differentially connected overcurrent	+	o	o	-	o
High-impedance differential	+	+	+	+	-
Low-impedance differential	+	+	o	+	+

+: excellent
o: good
- : Not good

Table 1: Comparison of bus differential schemes

As shown in Table 1 the high impedance bus differential protection offers the best performance regarding selectivity, speed, sensitivity and security. Unfortunately this scheme only works with dedicated CT which must be of same type and CT ratio. This is because in high impedance bus differential protection the current summation according to formula (1) is done externally. As this scheme is based on the characteristic of magnetic CT the use of process bus and NCIT technology has no advantages to this scheme.
Low-impedance differential schemes can reach nearly the same performance with much lower CT requirements. In these schemes CT's can be shared with other IED's and also CT's of different ratio can be used. However Low-impedance differential schemes are sensitive to CT-saturation. Special measures need to be implemented to gain stability of low-impedance differential protection in case of CT saturation.
Low-impedance differential schemes implemented in a microprocessor-based relay have the great advantage that Kirchhoff's current law according to formula (1) is applied on digitized data – no energy from the CT's is needed. Due to this principle the use of process bus and NCIT technology can further improve these kinds of bus protection schemes using NCIT which do not saturate for instance.

II. LOW IMPEDANCE BUSBAR PROTECTION

Low Impedance bus differential protection is based on Kirchhoff's current law. This law states that the sum of all currents flowing in and out of a protected zone is zero as long as there is no fault inside the protected zone. If there is a fault inside the protected zone the sum of currents will be different to zero.
For this reason an operating quantity called differential current I_{diff} is formed which is equal to the magnitude of the sum of all currents flowing into the protected zone:

$$I_{diff} = \left| \sum_{k=1}^{n} i_k \right| \tag{2}$$

In practical application this operating quantity I_{diff} is always unequal to zero due to effects like CT inaccuracy, CT trouble (broken wire, wrong connection) and CT saturation. Therefore a stabilizing component is necessary additionally.

$$I_{res} = \sum_{k=1}^{n} |i_k| \tag{3}$$

To increase the security of the algorithm a restraint current I_{res} is created according to formula (3) and a trip command is only given if the differential current exceeds a minimum differential current setting and a certain portion of the restraint current like shown in figure 2.

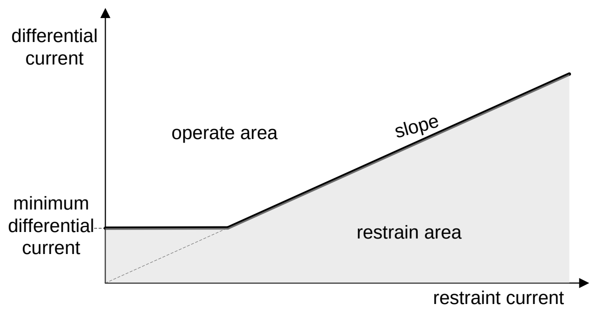

Figure 2: Typical trip characteristic of low impedance bus differential protection

In modern microprocessor-based relays two general kinds of algorithm of bus differential protection are implemented:

1. protection based on pure samples
2. protection based on current phasors

Bus differential protection based on pure samples only uses a few samples of fault current to form the differential and restrained quantities:

$$I_{\text{diff}} = \left| \sum_{k=1}^{n} \left(\sum_{l=1}^{m} i_{k,l} \right) \right| \tag{4}$$

$$I_{res} = \sum_{k=1}^{n}\left(\sum_{l=1}^{m}\left|i_{k,l}\right|\right) \quad (5)$$

k: consecutive number of bay / feeder
n: total number of bays / feeders
l: consecutive number sample
m: total number samples

Bus differential protection based on pure samples can generate a trip decision in a few milliseconds using a very short measurement window like shown in figure 3. A trip for this bus fault with high short circuit current can be given before the current transformer starts to saturate.

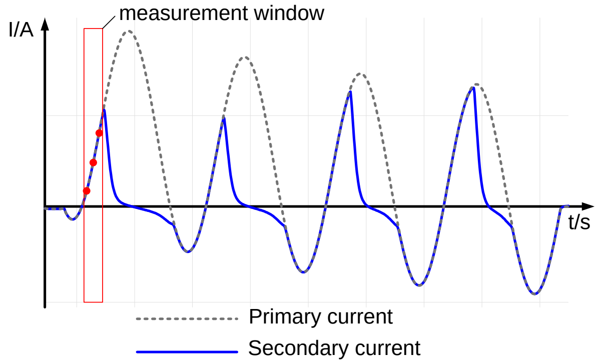

Figure 3: Measurement window for bus differential protection based on samples

Bus differential protection based on current phasors needs more time to generate a trip command because it needs a cycle of the fundamental frequency to calculate the current phasors. Finally, current phasors are used to form the operating and restraint quantities according to formula (6) and (7).

$$I_{diff} = \left|\sum_{k=1}^{n} \underline{I}_k\right| \quad (6)$$

$$I_{res} = \sum_{k=1}^{n}\left|\underline{I}_k\right| \quad (7)$$

Using current phasors instead of instantaneous values increases the sensitivity because the current phasors only contain the measurements of the fundamental frequency. All transients and the DC component are filtered out of the signal in best case.

III. CENTRALIZED VERSUS DISTRIBUTED BUSBAR PROTECTION

Dependent on the way how the data acquisition is realized two different architectures of low-impedance bus differential protection schemes are established today: Centralized and distributed bus differential protection.
For centralized bus differential protection all primary equipment like CT or auxiliary contacts of circuit breaker and disconnectors are connected via copper connections to the central unit like shown in figure 4. In this scheme all data processing is done in the central unit. Due to this approach centralized bus differential protection scheme is limited to approximately 20 bays. Centralized busbar protection is mostly cheaper compared to a distributed solution, because of less hardware and engineering effort.

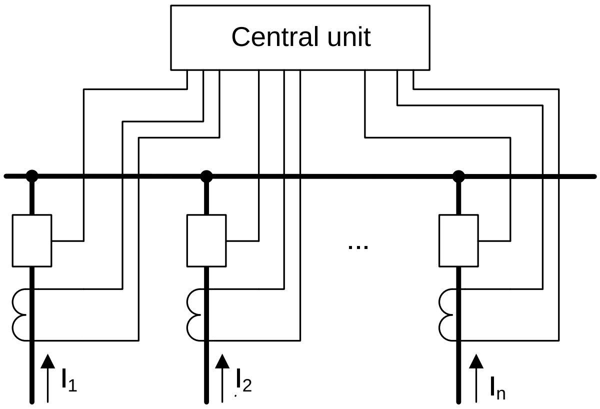

Figure 4: Architecture of centralized bus differential protection

The architecture of distributed busbar protection is shown in figure 5. Bay units are installed at each bay to get all relevant data from the connected bay. After pre-processing these data is sent via digital communication from the bay units to the central unit. The differential algorithm is running in the central unit. In case of a trip command this is transferred back to the bay units which give it to the connected circuit breaker.

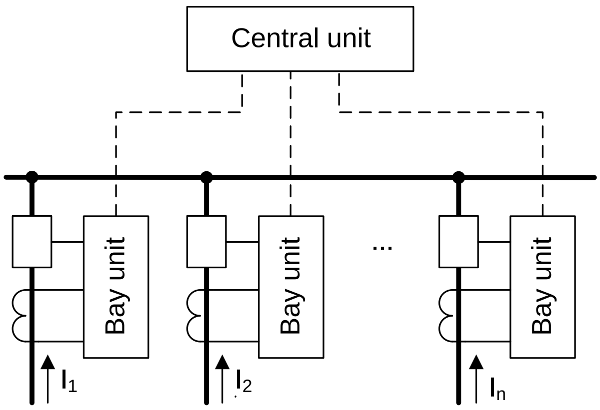

Figure 5: Architecture of distributed bus differential protection

The following characteristics support the use of distributed busbar protection:

1. Distributed busbar protection is especially applied at wide area air isolated substations. The wiring of primary CTs via a long-distance lead to a high burden of the CTs. A high burden of the CTs lead to an earlier saturation of the CTs, which is an inherent problem for differential protection
2. At distributed busbar protection a redundant feeder protection (CBFP, OCP, EFP etc.) in the bay units is possible.
3. Distributed busbar protection can typically cover a higher number of feeders.
4. Distributed busbar protection can typically easily be extended

Today it is possible to connect merging units to a centralized bus differential protection. Using this approach the difference between centralized and distributed bus differential protection will disappear.

IV. BUSBAR PROTECTION USING IEC61850

It seems obvious, that a distributed busbar differential scheme can be established using merging units as bay units and transferring the status of auxiliary contacts and trip commands via GOOSE messages. The concept of a merging unit as a function instead of a physical device enables a lot of different solutions. As shown in figure 6 a merging unit can be designed as a plain device only feeding the central device of bus differential protection with sampled measured values.

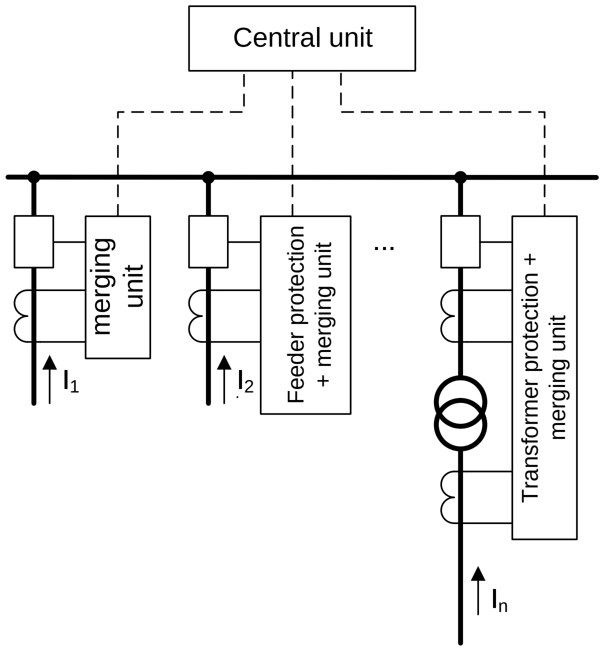

Figure 6: Architecture of distributed bus differential protection using plain merging units and merging units integrated in feeder or transformer protection devices

On the other hand the merging unit can be implemented in a feeder or transformer protection relay which main function is to protect the incoming or outgoing line or feeder. Delivering the sampled measured values to the central unit of busbar protection is an additional service only. This concept is used to save a lot of relays, wiring and engineering work.

Another solution is shown in figure 7. The same application as shown in figure 6 is designed in a different way. All bays are equipped with plain merging units and the bay specific protection functions are located in the central unit of bus differential protection. That means that feeder protection for bay 2 and also the transformer protection for bay n are running in the central unit of bus differential protection.

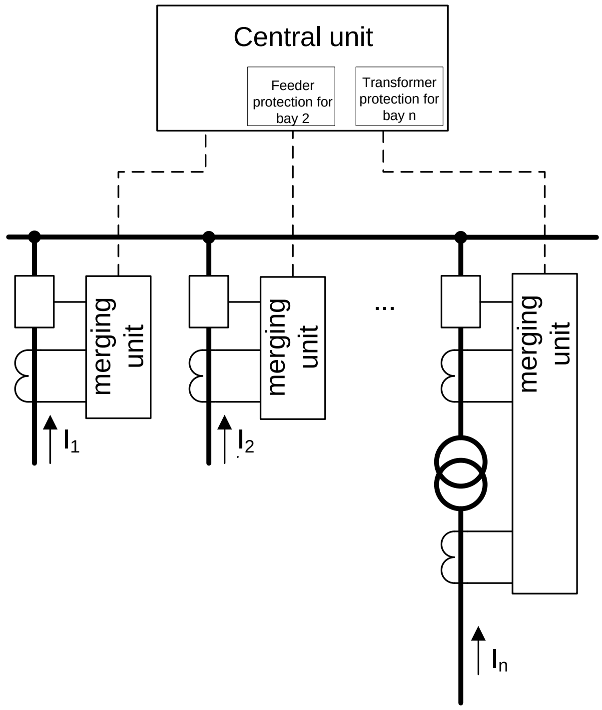

Figure 7: Architecture of distributed bus differential protection using plain merging units only

The use of merging units and IEC61850 enables a lot of different solutions for the communication architecture of a bus differential scheme. The classical proprietary solutions of distributed bus protection use field devices which are connected to the central device in a star architecture without any communication redundancy as shown in figure 8.

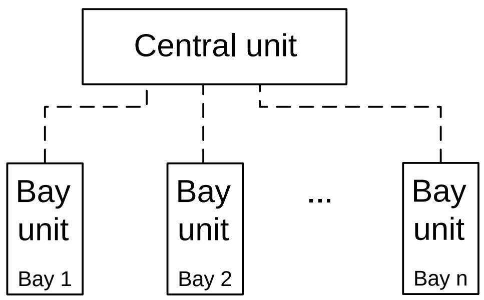

Figure 8: Communication architecture of classical distributed bus differential protection

A typical communication architecture of bus differential protection using IEC61850 is presented in [4]. The bay units shown in figure 8 are replaced by IED's containing the merging unit function and the capability to maintain binary signals from and to the relevant switchgear in the connected bay. These IED's are connected to an ethernet switch which is connected to the central unit of the bus differential protection like shown in figure 9.

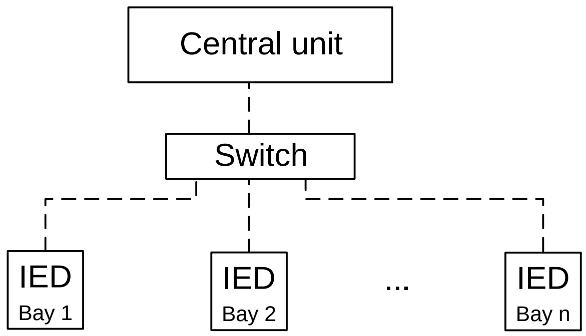

Figure 9: Communication architecture of distributed bus differential protection using IEC61850

If communication redundancy is needed each IED can be connected separately to two different switches which are connected in parallel to the central unit like shown in figure 10. This communication architecture is used for redundancy according to the PRP standard.

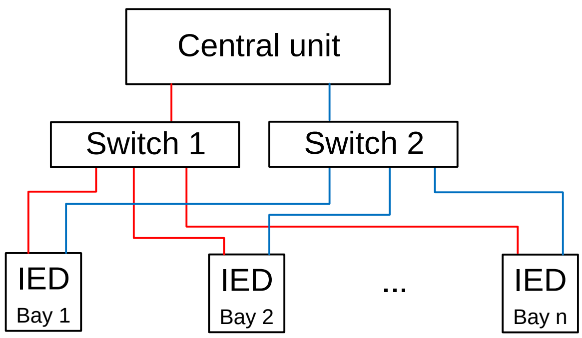

Figure 10: Redundant Communication of distributed bus differential protection using IEC61850 star structure according to PRP

Another solution for communication redundancy according to the Standard HSR is shown in figure 11. In this case the IED's acting as bay units of bus differential protection are connected in a communication ring with the central unit of bus differential protection.

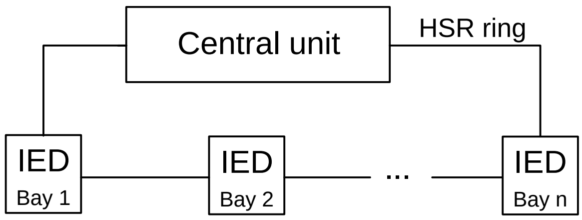

Figure 11: Redundant Communication of distributed bus differential protection using IEC61850 ring structure according to HSR

Additional to the communication redundancy a protection redundancy could be implemented like shown in figure 12. A second central unit of bus differential protection is added to the communication ring. This second central unit is able to receive the same data from the bay units and run redundant algorithm of bus differential protection.

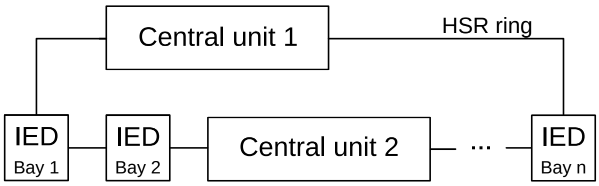

Figure 12: Redundant Protection for distributed bus differential protection using IEC61850 ring structure according to HSR

Time synchronization is utmost important for the proper function of a distributed bus differential scheme. Using sampled measured values according to IEC61869-9 the sampling of the currents in the different bay units has to be done at

the same instances of time with synchronization accuracy better than 1us.
Today the typical application for precise time synchronization is done using a commercial clock which can provide time synchronization according to IEEE 1588 with the power profile IEEE C37.238. This master clock is an additional device like shown in figure 13.

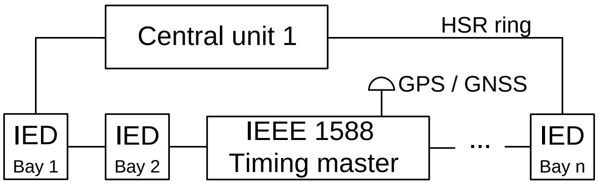

Figure 13: Time synchronization for distributed bus differential protection using IEEE 1588

Like discussed in [6] the reliability of a system based on IEC61850 depends on the composition of the system with different components.
Based on this calculation the reliability of a bus differential scheme based on IEC61850 is decreased due to the need of additional devices like GPS clocks and switches.
This problem can be solved by a different composition of the system. Like shown in figure 14 the master clock can be integrated in the central device of bus differential protection. The switches to form the HSR ring could be implemented in each IED.

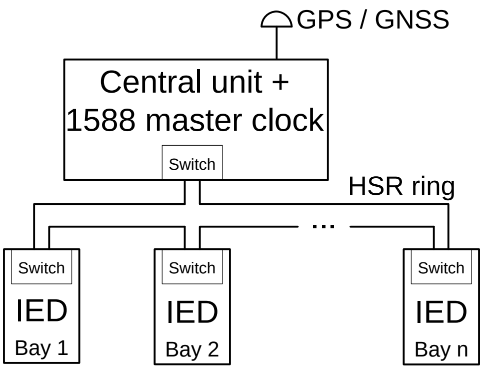

Figure 14: Integration of a master clock and switches in existing components of distributed bus differential protection

V. BUSBAR PROTECTION USING NON CONVENTIONAL INSTRUMENT TRANSFORMER

Process bus technology enables the possibility to use non conventional instrument transformer like optical current transformer or Rogowski coils for bus differential protection. These technologies have great advantages like higher accuracy and fewer problems with CT-saturation but there are also some constraints which have to be considered.
For a bus differential scheme with all measurement points using the same type of instrument transformer there should be less problems.
If different types of instrument transformers are applied in a bus differential scheme, care must be taken about the stability of the algorithm. The different transient behavior of different types of instrument transformers can produce a wrong differential current.
The transient behavior of instrument transformer is specified in IEC61869-6, Annex 6A [3]. Like shown in figure 15 an instrument transformer is permitted to transfer DC or is permitted to cut off the DC with a maximum high pass cutoff frequency of 1 Hz.

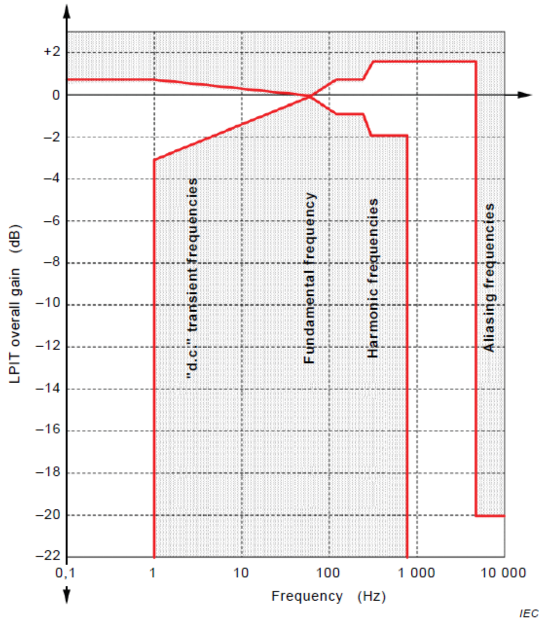

Figure 15: Transfer function for low power instrument transformer according to IEC61869-6

Based on this limitation a worst-case calculation can be done considering a fault current with 100% DC offset like shown in figure 16.
The blue curve in figure 16 represent the original fault current with 100% DC offset and a primary time constant of 60ms. This signal could be the output of an optical current transformer which is able to measure DC.

The red curve however is the output of a current transformer with the maximum permitted high pass cutoff frequency of 1 Hz.
The black curve is the difference between the output signals of both current transformers based on samples. This difference signal would appear as a differential current in a bus differential scheme.
The markers in the signals indicate samples with a sampling frequency of 1 kHz.

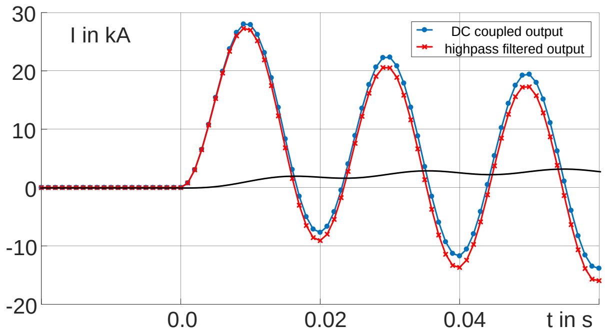

Figure 16: Output signals of two different CT for a fault current with 100% DC offset

Figure 17 shows the difference between the two extreme CT output signals in more detail. It can be seen, that for the first 3 samples after fault inception at t = 0.0 s the deviation of the high pass filtered signal compared to the DC-coupled signal is much less than 1% of the original signal.

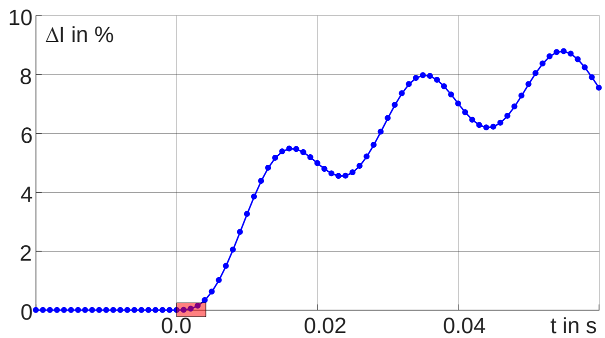

Figure 17: Difference between two CT output signals for a fault current with 100% DC offset

Using a differential protection algorithm based on samples according to formula (4) and (5) no additional stabilization would be necessary for the first samples. Using this algorithm for a longer time an additional stabilization of 10% should be applied.

In general it seems reasonable to use algorithm based on pure samples only for a short time after fault inception. After a full period algorithm based on current phasors reach a higher accuracy.
For phasor based bus differential algorithm the total vector error need to be covered by additional restrained current. For example the phasors are calculated using full cycle sinus and cosines filter. Figure 18 shows the total vector error based on the phasor deviation of both signals shown in figure 16.

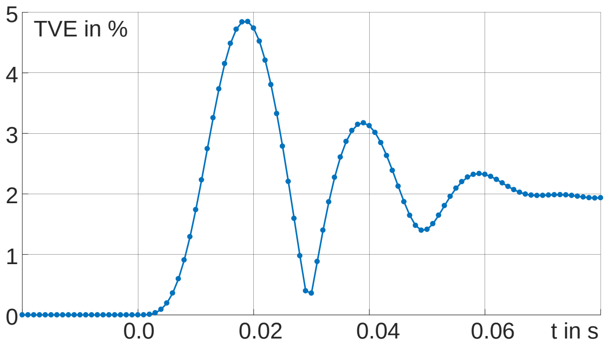

Figure 18: Total vector error of two CT output signals for a fault current with 100% DC offset

According to the coming standard IEC61850-7-4 edition 2.1 the high pass time constant of an instrument transformer with digital output should be given in form of a setting. Using this setting the signals coming from instrument transformers with different high pass time constants can be transformed to signals with the same time constant.
This could reduce the measurement error for bus differential protection using instrument transformer with different transient behavior.

VI. CONCLUSION

It was shown that process bus will have a great impact to the design of bus differential protection. Due to the concept of merging unit as a function instead of a box, different schemes of centralized or distributed protection becomes possible. Process bus also enables the use of NCIT for low impedance bus differential protection.

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VIII. BIOGRAPHIES

Rainer Goblirsch received his diploma of physics from the Friedrich Alexander University Erlangen in 1992. He worked for several years in the development for substation automation and protection. He was project lead for several protection devices and in the last years mainly for busbar protection devices and systems. Since 2014 he is the Product Manager for Siemens Busbar Protection Relays.

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