Interoperability of Line Differential Protection

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Abstract

Line differential protection is used for a long time to protect overhead lines and cables in transmission and distribution systems. The basic principle of line differential protection is Kirchhoff's current law. Due to this principle line differential protection is strictly selective to clear faults on the protected line.

To apply Kirchhoff's current law a line differential protection needs the currents from both ends of the protected line. The currents from the local end can be measured directly by means of current transformers, connected to the line differential protection device. The remote end currents however cannot be measured directly by the local line differential protection device. In general, the remote end currents are measured by a line differential protection device of same type and afterwards sent via communication link.

Due to bandwidth restrictions of the communication link, differences in pre-processing of the measured values and other device specific implementations there is no interoperability of line differential protection. In general line differential protection requires both devices to be from the same manufacturer. Often the same device type or even the same firmware version is required. Today there is no interoperability for line differential protection. In case one substation gets an update of the line differential protection, the remote substation needs an update of the related line differential protection too.

This paper describes an actual case how interoperability was achieved for line differential protection of different protection platforms of one manufacturer. The problems and limitations for this use case are explained in detail.

In addition to this the paper suggests an implementation of line differential protection based on sampled measured values and GOOSE according to IEC61850 and IEC61869. With this approach, the communication interface between the line differential protection devices becomes interoperable. More flexible solutions are found to be possible. For instance, a line differential scheme might consist of only one line differential relay, receiving sampled measured values from a merging unit located at the remote end. The trip command for the remote end might be transferred back via GOOSE to the merging unit located at the remote end. For redundancy even two different line differential protection relays could be used feeding each other with the sampled measured values from the remote end.

1 Introduction

Line differential protection is based on Kirchhoff's current law. This law states that the sum of all currents flowing into a protected line is zero if there is no fault on the protected line:

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

k: consecutive number of line ends
n: total number of line ends

Due to this principle line differential protection is strictly selective to clear faults on the protected line.

Figure 1 illustrates the operating principle of line differential protection in case of an internal fault. To calculate the operating quantity $\Delta\underline{I}$ the line differential protection needs to measure the current phasor $\underline{I}_A$, flowing into the protected line coming from bus A and the current phasor $\underline{I}_B$, flowing into the protected line coming from bus B.

It seems obvious that for an internal fault the operating quantity will become high enough to detect the fault and trip the faulted line.

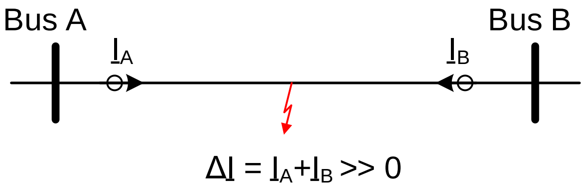

Figure 1: Operating quantity of line differential protection in case of an internal fault

Figure 2 illustrates the situation in case of an external fault. For an external fault the operating quantity $\Delta\underline{I}$ is very small because the current $\underline{I}_A$, flowing into the protected line coming from bus A is leaving the protected line at bus B as $(-\underline{I}_B)$.

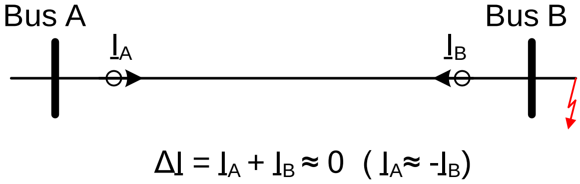

Figure 2: Operating quantity of line differential protection in case of an external fault

Figure 1 and Figure 2 illustrate the calculation of the operating quantity based on current phasors. There are other implementations using sampled measured values of currents or polarity of currents to calculate the operating quantities.
Nevertheless, all these algorithms require a synchronization of the current measurement on both line ends.
Using analog technology, the secondary output of the current transformer is transmitted to the remote end via cables in parallel to the protected line. Due to this principle the maximal length of a line to be protected by a line differential protection is limited as explained in [9].
With digital technology lines longer than 100 km can be protected by line differential protection.

Line differential protection is using an operating quantity called differential current Idiff which is equal to the magnitude of the sum of all currents flowing into the protected zone according to formula (2):

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

$$I_{res} = \sum_{k=1}^{n} |i_k| \quad (3)$$

In practical application this operating quantity Idiff is always unequal to zero due to different effects.

- Primary system (charging currents, tapped loads)
- Current transformers (measurement inaccuracy, CT-saturation, broken wire)
- Measurement pre-processing (AD conversion, filtering)
- Time synchronization

To increase the security of the algorithm a restraint current Ires is calculated 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 3.

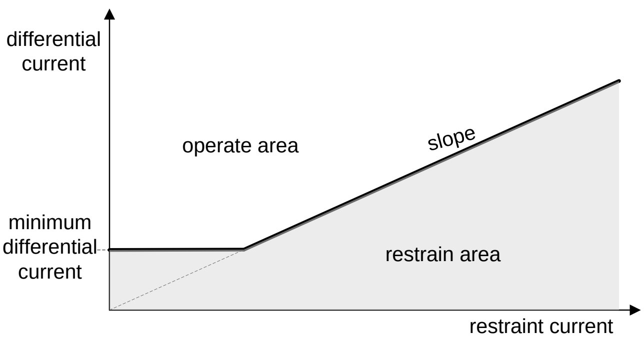

Figure 3: Typical trip characteristic of line differential protection

The slope of the restrain characteristic is often focused on the measurement accuracy of the primary current transformer like applied as the dual slope characteristic. However other influencing factors like measurement pre-processing chain and synchronization accuracy need to be considered too.

2 Interoperability problems of line differential protection

A line differential scheme requires a separate device for each end of the protected line. To protect the line between bus A and bus B as shown in figure 4 two devices are necessary. Device "Diff A" measures the current $\underline{I}_A$ and issues a trip command to circuit breaker CB_A when detecting an internal fault. Device "Diff B" measures the current $\underline{I}_B$ and issues a trip command to circuit breaker CB_B when detecting an internal fault.

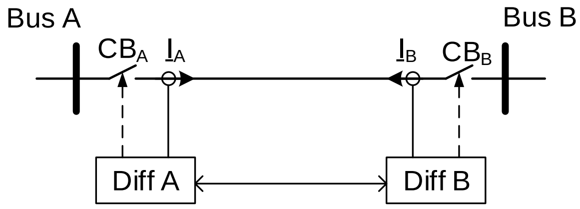

Figure 4: Basic principle of a digital line differential protection

The line differential protection algorithm can run in both devices (Multi master mode) or in one device only (Master slave mode). In both cases a communication link between both devices is necessary to transmit the current measurements and additional binary information. This communication link is normally also used for the synchronization of the current measurement which is utmost important for line differential protection.
The major difficulty is the simultaneous measurement at all ends of a line differential protection scheme. This requirement is solved by means of clock synchronization of all devices.
Due to this composition of the function a line differential protection scheme in general requires devices of same type delivered by the same manufacturer and often even having the same firmware version.
To achieve interoperability of line differential protection the following topics need to be considered.

2.1 Measurement pre-processing

According to figure 1 and figure 2 the algorithm of a line differential protection needs the primary currents from both line ends. This is not possible in practical applications.
The primary current is converted to a secondary current on both ends of the line using a current transformer. This current transformer already has an impact on the current measurement used by the line differential protection algorithm. For practical applications it is recommended to use the same primary current transformer class on both ends. This is because all differences introduced into the current measurements appear as a differential current. For line differential protection based on digital relays the current measured by the primary current transformer is converted to a digital data stream and transferred to the remote end. The process of A/D conversion and phasor measurement also impact the current measurement.

Generally spoken the entire measurement chain like shown in figure 5 including primary current transformer, secondary current transformer, filtering, amplification, A/D conversion and time stamping needs to be considered for interoperability of line differential protection.

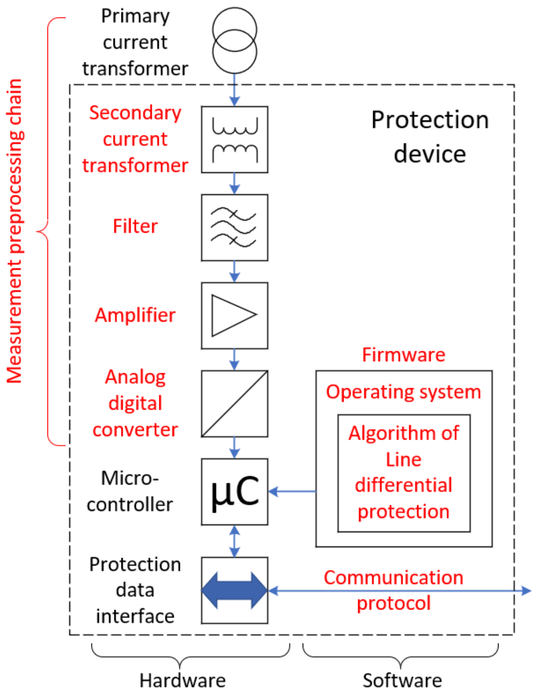

Figure 5: Factors (in red color) influencing the interoperability of line differential protection

2.2 Algorithm

According to [5] there are different methods of line differential protection. Phase comparison is a method optimized for low bandwidth requirements. This method only uses the information about the sign of the alternating current signal.
Beside this there are different techniques using current phasors. These techniques are very sensitive but not extremely fast because at least a power system cycle is needed to calculate a current phasor of high accuracy. To achieve a faster trip time there are different techniques based on sampled measured values.
It seems obvious that these algorithms have different requirements to the measurement pre-processing and communication within the line differential protection scheme.

2.3 Communication

Today the communication protocol for line differential protection is not standardized. Different relays use different protocols, optimized for low bandwidth requirements and high performance for the specific algorithm of line differential protection. That’s why all line differential relays use proprietary communication protocols which are tight knit with the implemented line differential protection algorithm.

2.4 Firmware version

Improvements in the line differential protection algorithm and changes also in the operating system sometimes might lead to incompatibilities between newer and older firmware versions.

3 Interoperability of line differential protection between SIPROTEC 4 and SIPROTEC 5

Starting with the year 2000 SIEMENS delivered line differential protection based on the platform SIPROTEC 4. Up to now there are more than 100,000 of these relays installed.
In 2012 SIEMENS launched a line differential relay based on the new platform SIPROTEC 5. The new line differential relay based on SIPROTEC 5 uses in general the same method for line differential protection. In detail however there are some improvements of the algorithm compared to SIPROTEC 4. Additional to this also the hardware including measurement pre-processing was designed completely different.
Based on the great number of installed relays there was a pressure coming from the market to gain interoperability between line differential protection devices based on SIPROTEC 4 and SIPROTEC 5. Customers which are planning to upgrade their system substation by substation or customers owning only one substation of a line differential scheme asked for an interoperability between SIPROTEC 4 and SIPROTEC 5. This interoperability would allow them to change only one device of the line differential scheme.
Finally, an interoperability mode was implemented into the line differential protection relay SIPROTEC 5 as explained in the following sub-chapters.

3.1 Measurement pre-processing

The measurement pre-processing chains in both product families are different. In detail, the secondary current transformer, the A/D converter, the frequency response of filters and the pre-processing time are different.
Knowing the transfer function of the measurement chain in SIPROTEC 4 a compensation for the current phasors was implemented in SIPROTEC 5 line differential protection.
Figure 6 shows the remaining phase shift or time base offset between the measured currents of two devices for different current values at nominal current of 1A.

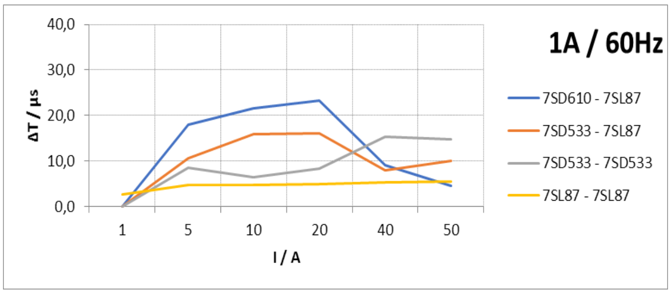

Figure 6: Remaining Phase shift / Time base offset between SIPROTEC 4/5

The remaining phase shift between devices of the same type is quite small. For the combination of different device types, the remaining phase shift after compensation is higher but still acceptable.
Figure 7 shows the differential current for an external fault with a large DC offset based on current samples. Due to the different time constants of the secondary current transformer in SIPROTEC 4 and SIPROTEC 5 there is a remarkable differential current especially for algorithm based current samples. For practical applications this is not important because these algorithms are only active for a limited time after fault inception.

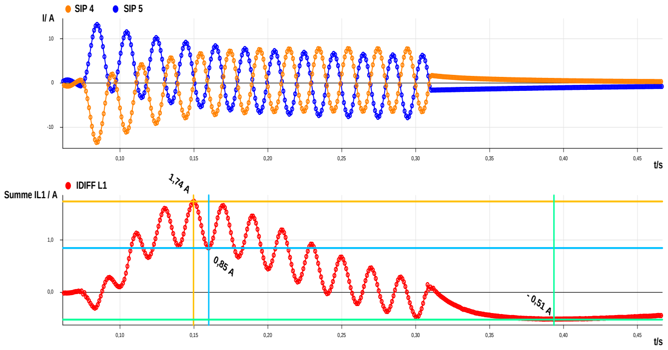

Figure 7: Current difference based on sampled measured values between SIPROTEC 4/5

All effects of different measurement pre-processing cannot be corrected completely. For that reason, SIEMENS recommends increasing the slope of the restrain characteristic of the line differential protection function according to the primary CT class.

3.2 Algorithm

In general, the line differential protection in SIPROTEC 5 uses the same method like the line differential protection in SIPROTEC 4. However, there are functionalities in the SIPROTEC 5 line differential protection which are not available in the SIPROTEC 4 line differential protection and vice versa. The simple diagram shown in figure 8 explains the area of interoperable algorithm.

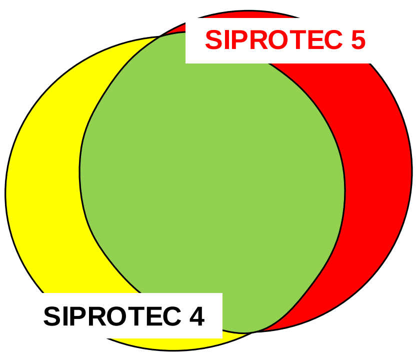

Figure 8: Area of interoperability between SIPROTEC 4/5

Interoperability is only reached in the green marked area for functionality which is implemented in SIPROTEC 4 and SIPROTEC 5. For example, the Difference Current Supervision is only available in SIPROTEC 5. Therefore, Difference Current Supervision is not working together with SIPROTEC 4 in the interoperable mode.
Regarding the trip times SIPROTEC 4 and SIPROTEC 5 devices in interoperability mode reach the same trip times as SIPROTEC 4 devices or SIPROTEC 5 reach independent from each other.

3.3 Communication

The communication protocols of the line differential protection in SIPROTEC 5 was enhanced to support new functionality only available in SIPROTEC 5. To reach interoperability with SIPROTEC 4 a special mode was implemented which supports the interoperability to SIPROTEC 4.

3.4 Firmware version

The interoperability of line differential protection between SIPROTEC 4 and SIPROTEC 5 was not implemented from the beginning but starting with a certain firmware version.
During the start-up both devices exchange their firmware versions. If both versions are interoperable, the functional behaviour of the local device can be switched according to the firmware version of the remote device.

4 Evaluation of existing standards regarding interoperability of line differential protection

Measurement pre-processing and communication protocols have the greatest impact to the interoperability of line differential protection. Today there is no standardization for measurement preprocessing and communication protocol of line differential protection. But there are other standards defining measurement preprocessing and communication protocols which could be used for line differential schemes. Table 1 shows an evaluation of two existing standards regarding their usage in line differential schemes.

	IEEE C37.118	**SMV according to IEC61950 and IEC 61869**
Measurement quantity	phasors	sampled measured values
Measurement accuracy	1% total vector error	Accuracy classes
Reporting rates	up to 60 Hz	4800 Hz
timing accuracy	≈1us	1us
Measurement reference	primary value in A	primary value in A

Table 1: Evaluation results of existing standards regarding usage in line differential protection

Both standards do not standardize the transfer function of the measurement pre-processing chain itself but standardize a certain measurement accuracy which is sufficient for the interoperability of line differential protection. The measurement reference, the time stamp of the measurement is related to the primary values in both cases with an accuracy around 1 microsecond.
IEEE C37.118 [6, 7] defines synchrophasors with a synchronization accuracy of ≈1us and a total vector error of 1% related to the primary current. This accuracy is sufficient for line differential protection.
Due to the exchange of standardized synchrophasors line differential schemes based on IEEE C37.118 are limited to algorithm based on phasors only. The maximum reporting rate of 60 Hz is an additional limit to the trip time of such scheme.
Using sampled measured values according to IEC 61850 [2] and IEC 61869 [3, 4] gives more flexibility to the implementation of a line differential scheme. With sampled measure values as input all known algorithm of line differential protection can be implemented.
The timing accuracy of 1µs and the sampling rate of 4800 Hz are sufficient for all known line differential protection methods based on phasors and sampled measured values. According to the accuracy requirements of the line differential scheme a certain accuracy class of the merging unit can be chosen.

5 Interoperable line differential protection using IEC61850

In [1] a 2-terminal current differential feeder protection relay is modeled as shown in figure 9.

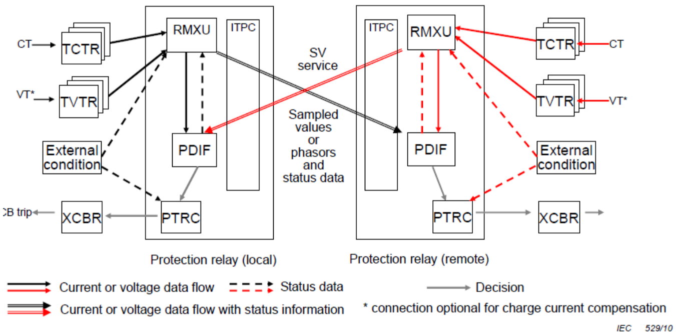

Figure 9: 2-terminal current differential feeder protection relay model according to IEC 61850-90-1

This model is excellent to explain all existing implementations of line differential protection relays by terms of IEC 61850.
Regarding interoperability there is only one interface between both devices. The logical node RMXU in one relay is sending data to the logical node PDIF in the relay at the remote end.
The logical node RMXU provides phasors or samples representing the local current values. RMXU on both sides of the line represents also the function to synchronize the samples or phasors.

As explained in chapter 4 sampled measured values are more flexible than phasors for the implementation of a line differential scheme. All known algorithm of line differential protection can be chosen according to protection requirements like sensitivity or trip time.
Using only sampled measured values the logical node RMXU can be replaced by logical nodes TCTR which are already delivering synchronized sampled measured values according to IEC 61850-9-2 [2] and IEC 61869-9 [4].
Figure 10 shows a simplified diagram of an interoperable line differential protection scheme. This scheme consists of two devices based on the same model. However, interoperability is achieved by using only sampled measured values and GOOSE as standardized interface between both devices.

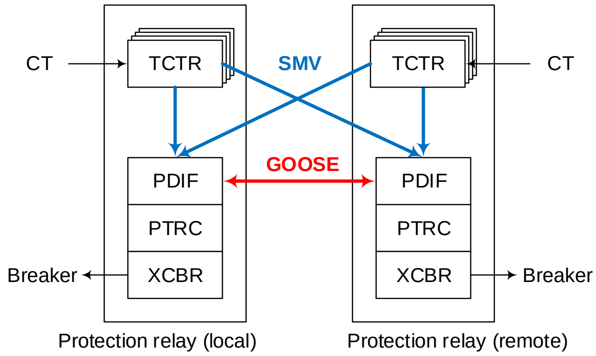

Figure 10: Interoperable line differential protection scheme using two similar devices

Logical nodes TCTR are connected to the primary CT`s. These logical nodes TCTR are delivering synchronized sampled measured values to the logical node PDIF in the local protection relay and in the remote relay. Based on these sampled measured values the algorithm of line differential protection is running in the local and remote relay in parallel. If necessary, status information can be exchanged between the logical nodes PDIF in the local and remote relay using the R-GOOSE mechanism.
If the line differential protection PDIF detects an internal fault it will send an operate signal which is converted to a trip command for the connected circuit breaker by the logical nodes PTRC and XCBR.
In general, it is not necessary to run the same algorithm of line differential protection with the same data in both devices. Figure 11 shows a line differential scheme with only one line differential relay and a merging unit.

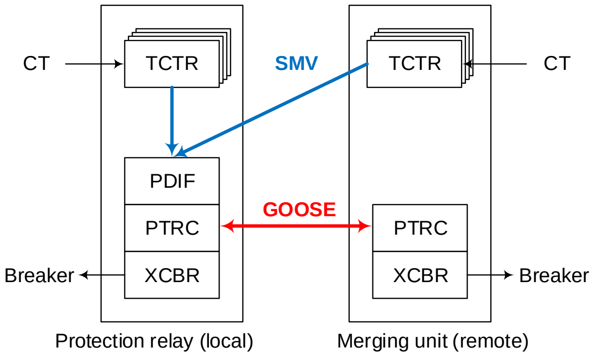

Figure 11: Interoperable line differential protection scheme using one line differential protection relay only and a merging unit

In this scheme the line differential relay is receiving sampled measured values from a merging unit located at the remote end. The trip command for the remote end might be transferred back via GOOSE to the merging unit located at the remote end.
For redundancy even two different line differential protection relays could be used feeding each other with the sampled measured values from the remote end. Figure 12 shows an example for a line differential scheme with line differential relays originating from two different manufacturers.

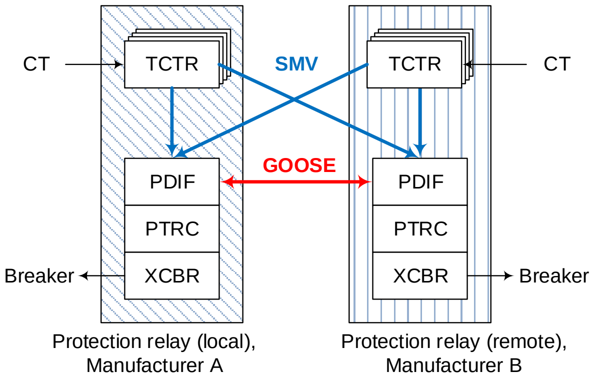

Figure 12: Interoperable line differential protection scheme using two line differential protection relays from different manufacturers

Due to the exchange of sampled measured values also different algorithms can run in the relays at local and remote end. For instance, a sensitive current differential algorithm could be combined with a fast phase comparison algorithm.
In any case both relays should share the operate signal with the remote end. Based on the local and remote operate signal a trip command for the breaker could be given if any algorithm gives an operate or only if both algorithms give an operate signal.

Communication aspects

Today the available bandwidth of communication systems is increasing permanently. Thereby now it becomes possible to transmit sampled values in real time via great distances.

Communication problems like data packet loss, switching of the used communication path or long response times can occur. But these problems are not related to the interface between the line differential relays. These problems also occur, if a line differential protection scheme is using a proprietary communication interface via a switched network.
If data packets are lost or delayed, the line differential protection must react in a specific manner.

Time synchronization

The synchronization of the current measurement is utmost important for the function of line differential protection. Today synchronization is done by proprietary methods based on the so-called ping-pong method via the proprietary protection data communication. In the proposed solution the function of time synchronization is taken over by standardized solutions based on IEEE1588.

Conclusion

Interoperability is an important issue for line differential protection. It was shown that later implementation of interoperability into existing relays is possible with certain restrictions.
For future applications it was suggested and explained to achieve interoperability of line differential protection by using sampled measured values and GOOSE.

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