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Impact of measurement and communication aspects on protection of multi-terminal DC grids

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Abstract: The increased demand for renewable energy generation requires the higher flexibility of transmission systems. This requirement together with technical progress in high-voltage DC technology has resulted in the ambition to build large-scale multi-terminal DC grids. To achieve this goal, vendor interoperability is considered a key element. Standards exist for AC systems, but not for DC systems. This work discusses and evaluates the suitability of AC standards for DC systems. As a result, a different view on substation architecture is developed and two communication protocols are suggested for further investigation in this context.

1 Introduction

System protection for multi-terminal DC (MTDC) grids has to be reliable and fast. The inherently low impedance in high-voltage DC (HVDC) is a challenge for MTDC system protection. Several fault detection algorithms [1] and fault clearing strategies [2] have been proposed. An example of an MTDC grid using DC breakers is shown in Fig. 1.

After a fault has occurred in an MTDC grid, first the fault has to be detected. After that, and for the fault clearing to be selective, the correct protection action has to be initiated. DC busbar fault detection requires measurements from all lines connected to the busbar. Line fault detection can rely on locally measured signals and/or on signals from the remote line end [3]. An accurate time stamp is most likely required for fault detection using data from the remote line end. The measurement sampling frequency can have an impact on fault detection speed depending on which fault detection criterion is used. The local line fault detection algorithm in [4] uses several criteria, among them undervoltage and voltage derivative. The required filtering in [4] introduces an additional delay which is negligible compared with the breaker opening times. For the system in [4], sampling frequencies of at least 50 kHz achieve the fastest fault detection times.

Ultimately, one or several of the following three immediate protection actions have to be performed with corresponding operating times:

- *AC breaker opening*: in the range of $t = 40$ ms [5].
- *DC breaker opening*: hybrid and active resonants are fastest, need at least the opening time of the mechanical switch today around $t = 2$ ms [6].
- *Converter blocking*: based on arm current, initiated by the converter controller.

Also, the operation of further equipment, e.g. residual current breakers and/or a change of converter control mode might be required.

Today, the control and protection system in an HVDC substation is generally supplied by a single vendor. Therefore, fault detection algorithms for the DC side would be executed in one central intelligent electronic device (IED) unit in the substation as shown in Fig. 2. For dependability in case one IED fails, two identical IEDs would be operated in parallel [7, 8].

This centralised approach is inherently vendor dependent. Compatibility between equipment from different vendors, however, is considered a key enabler for building an MTDC grid. The underlying aspects have been discussed in [9]. An alternative approach with several, decentralised IEDs is shown in Fig. 3. Every breaker has its own IED that receives local voltage and current measurements as well as communicated information from other IEDs in the substation.

Measurement and communication aspects are expected to influence the system protection of MTDC grids. Communication is often assumed to be too slow for MTDC grid protection without referring to an actual communication method. This work focuses on substation communication and measurement aspects and their impact on MTDC protection.

There are two approaches for evaluation: (a) to design a system protection and then deduct measurement and communication requirements or (b) to observe existing standards and protocols and evaluate whether these might be suitable for MTDC protection. Approach (b) is chosen in this paper. Sections 2 and 3 present existing measurement and communication standards and protocols. Their suitability is discussed in Section 4. The conclusion is drawn in Section 5.

2 Measurement

In HVDC, non-conventional instrument transformers are used for measurement of DC quantities. Their standard sampling rate is stated with 96 kHz [10] in IEC 61869-9 (digital interface for instrument transformers DC high bandwidth). Voltage measurements are taken by resistive-capacitive (RC) voltage dividers [11]. Current measurements can be taken either by hybrid electro-optical sensors [7], fibre optic current sensors or zero-flux sensors [4]. The devices mentioned here are expected to achieve the sufficient bandwidth for sampling at 96 kHz.

Optical measurements internally quantise and sample the measured value. The interface from an optical instrument transformer has to be digital [12] and should not be analogue. If the interface was analogue (as widely done in AC instrument transformers), first a digital-to-analogue conversion in the instrument transformer, and then an analogue-to-digital conversion at the input of the control device or IED would be required. Possible involved non-linearities, amplifier behaviour and current limitations would lead to loss of information.

In [13], a word length of 32 bit for voltage or current measurement is suggested with 1 mA and 10 mV as least significant bit and 1 bit used for sign representation. This results in a range of

- *Current*: ± 1 mA to $\pm (2^{32-1} \times 1$ mA$) = \pm 2147$ kA.

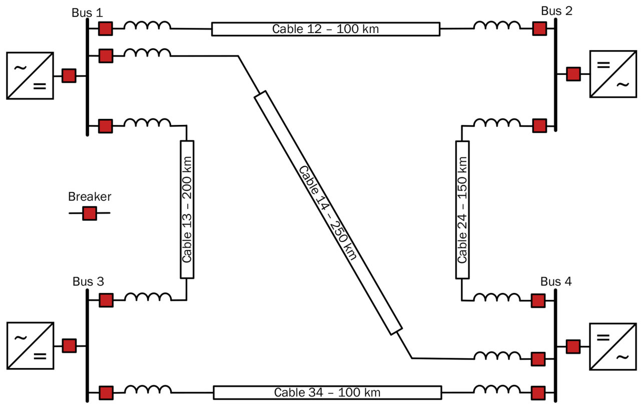

Fig. 1 *MTDC grid example*

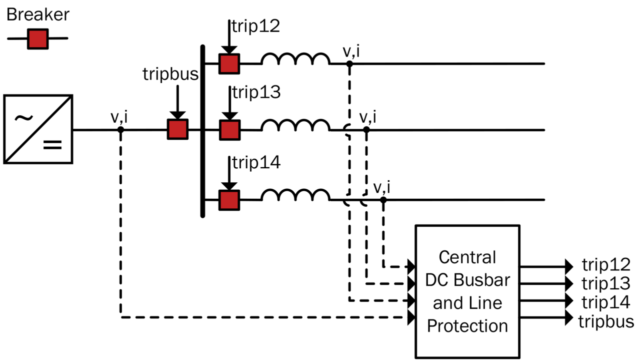

Fig. 2 *Central IED*

- *Voltage*: ± 10 mV to ± $(2^{32-1} \times 10\text{ mV}) = \pm 21{,}475$ kV.

The dynamic range in MTDC grids is covered by this representation.

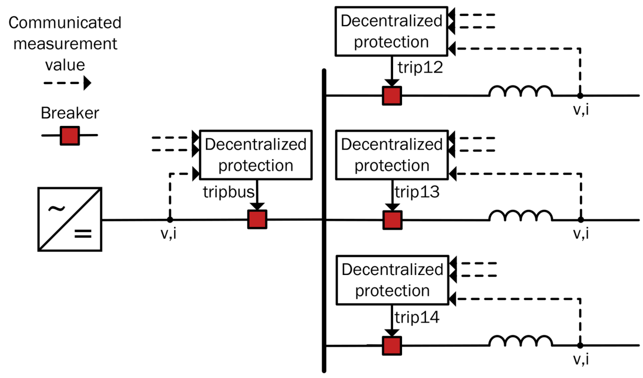

Fig. 3 *Decentral communicating IEDs*

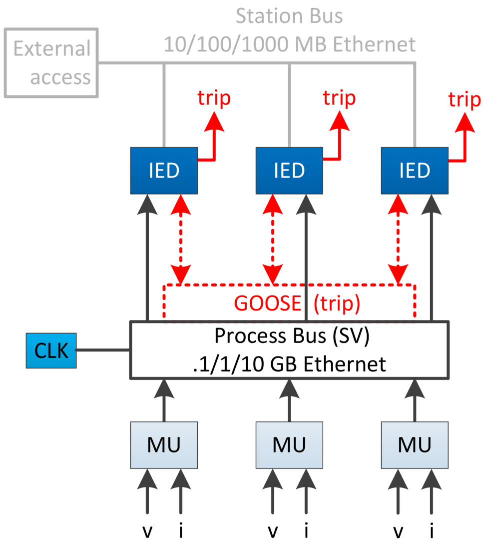

Fig. 4 *Substation architecture in IEC 61850*

3 Communication

The conventional architecture in traditional (AC) substation communication is to use separate systems for protection, metering and operation. Functions are tied to physical devices and connections to current and voltage transformers are based on point-to-point (copper) links. This makes such an arrangement inflexible and complex unless standards are specified. The 'digital substation' approach shall reduce cabling and enable interoperability between protection relays. Furthermore, this concept achieves more flexibility and vendor independence by making use of standardised technologies such as Ethernet. The approach for a digital substation in AC is outlined in IEC 61850 (Communication networks and systems for power utility automation). An open question is in how far this standard can be applied to an MTDC substation.

3.1 Communication standard

3.1.1 IEC 61850 Communication networks and systems for power utility automation: In IEC 61850, the information model is separated from its protocol implementation. This improves vendor interoperability and thus independence. The IED is not only responsible for protection, but can also report events and measurement data, communicate horizontally with other IEDs and include control functions. A possible substation architecture using IEC 61850 is shown in Fig. 4.

IEC 61850-8-1 defines the generic object oriented system event (GOOSE) message for application layer horizontal communication between IEDs based on a publisher–subscriber model. This means that a GOOSE message is sent as multicast within the substation network. To ensure the reception of the message by the receiving IED, the GOOSE message is published repeatedly at a declining rate. A GOOSE message consists of mostly binary information, e.g. trip signals. Since GOOSE usually uses Ethernet at the data link layer, there is no confirmation of the successful reception of a message implemented.

The implementation guideline [13] (also known as IEC 61850-9-2 LE, LE for light edition) specifies the sampled value (SV) message as follows: SV uses sampled data from current and voltage measurements in a device called merging unit (MU) at the process level. The MU transmits three-phase and neutral current and voltage measurements at a sampling rate of 80 samples per cycle for protection and 256 samples per cycle for measurements functions. However, the samples intended for protection purposes are published directly and individually on the process bus, whereas the samples intended for measurement purposes are stacked to a batch of eight samples and then published together. In a 50 Hz system, a new sample for protection is thus published every 250 µs. A new batch containing eight measurement samples is published every 625 µs. The messages are sent to bay level via an Ethernet frame using a publisher–subscriber model. SV messages from an MU need a time reference with ±4 µs accuracy coming from a time source giving a signal of 1 PPS and an accuracy of ±1 µs [13]. The communication delay of an SV message through the process bus has to be below 3 ms. Also, the required recovery time of the communication link needs to be bumpless, meaning zero time for recovery.

IEC 61850-9-2 LE furthermore states [13]: 'No specifications are made with regard to physical devices (IEDs). An IED may consist of more than one logical device MU sharing the same communication interface'. This means that both central IED and several decentral IEDs (and MUs) are possible.

3.1.2 IEEE 1588 Precision time protocol: IEEE 1588 defines a network-based time synchronisation technique designed to coexist with IEC 61850 applications with sub-microsecond timing accuracy.

Timing accuracy is important, especially in differential protection. On substation level, either many dedicated optical fibres can be used to distribute global positioning system (GPS) time or many distributed GPS receivers can be used [14]. Both can be unpractical and expensive. In [14], it is suggested to use 2–3 GPS master clocks per substation and an Ethernet network with synchronisation based on IEEE 1588-2008 standard. In this, the 1588-traffic shares the Ethernet with IEC 61850 SV and GOOSE applications. A special profile of the precision time protocol for the power utility industry has been defined in IEC 61850-9-3.

The conclusion in [14] is that substation data networks with IEEE 1588-clocks and IEEE 1588-capable Ethernet switches can achieve synchronisation accuracy below 1 µs even when heavily loaded. This depends, however, on the actual IEEE 1588 switches and hardware time stamping of all involved network devices as well as slave implementation and communication protocol. For example, the impact of high-availability seamless redundancy (HSR) protocol (see Section 3.2.1) on long-term timing accuracy when used with IEEE 1588 is up to 122 ns/24 h. However, HSR link loss does not affect timing accuracy.

3.2 Communication protocols

3.2.1 High-availability seamless redundancy: HSR [15] (as defined in IEC 62439-3) is a protocol that is mostly used at the bus level process of AC substations. A single communication failure in an HSR ring does not lead to data loss. Furthermore, the recovery time is zero in case of a communication failure. All devices are arranged in a ring. A message from a sending device is sent in both directions in the ring. The receiving device reads the first version that arrives and ignores the other one. Messages that are not intended for a particular device are forwarded (unless they have already been forwarded if so, they are discarded). If one communication link fails, the message can still be received from the other direction in the ring. This means that the paths are slightly different which results in slightly different transmission times. Also, the transmission times depend on the number of devices in the ring, but are considered to be a fraction of a millisecond [15]. The number of devices in a ring is limited by the port with the smallest bandwidth (usually 100 Mbps). This results in maximum 20 devices for a station bus and maximum 6 devices for a process bus publishing only SV [15]. One potential problem with HSR is that HSR frames are not compatible with standard Ethernet frames. Also, if one device shuts down, e.g. for maintenance, the broken ring needs to be closed manually [15]. The conclusion in [15] is that HSR rings are suited only for small self-contained sections of an AC substation.

3.2.2 EtherCAT: EtherCAT [16] is a hardware-augmented real-time Ethernet-based communication protocol, which utilises a master–slave concept. All slaves in the network can read from a passing EtherCAT frame and write data to it as the frame passes in a daisy-chain fashion. Taking advantage of this ‘logical addressing’ enables many slaves to work with only one EtherCAT frame. Once the frame reaches the end of the network, it is sent back to the master. Therefore, even if complex topologies such as star or tree can be built, they are equivalent to a line topology. EtherCAT frames are standard IEEE 802.3 Ethernet frames with 64–1518 B length. If the data to be transmitted does not fit into one frame, it can be split into several frames. Also, EtherCAT components can work with standard network interfaces, but in practise the slaves use special hardware to achieve short packet forwarding time [17]. The delay at each slave is independent of the frame size. A constant slave delay of below 0.5 µs is assumed in [17]. EtherCAT masters are usually implemented with standard components (i.e. not hardware augmented [17]). Today, 100 Mbps network speed is available. The protocol, furthermore, provides slave synchronisation below a few hundreds of nanoseconds (as mentioned in [17]), as well as redundancy with recovery times below 15 µs [16]. Hot swap of devices and hot connect of network segments is possible if the master is configured accordingly. Also, EtherCAT is an open standard which is advantageous for interoperability.

Consider substation 1 as depicted in Fig. 3: the proposed architecture consists of one breaker IED for each breaker. Every breaker IED receives local current and voltage measurements and acts as an EtherCAT slave which communicates with other IEDs. The slaves can be arranged in a ring. This means that $2\times4=8$ slaves would be required for positive and negative poles with three lines and one busbar measurement each. Each slave sends locally measured voltages and currents and receives measured values from other EtherCAT slaves through the master after one communication cycle. The total amount of communicated data samples (without additional information) would then be $2\times8\times32$ bit = 512 bit. This easily fits into one EtherCAT frame with plenty of additional space for binary information, e.g. status bits or trip signals. The cycle time for such an arrangement is calculated as follows:

$$T_{\text{line(1 frame)}}^{\text{EtherCAT}} = T_{\text{master}} + n\,T_{\text{slave}} \quad (1)$$

with

- $n=8$ slaves.
- T_{master}: master forwarding delay (including forwarding time of a packet at the master and physical layer delays).
- T_{slave}: maximum slave forwarding delay (both directions including slave implementation delay, physical layer delays and fibre propagation delay) of 1 µs [17].

Depending on the master implementation, the cycle time would be a few tens of microseconds. The estimation in [17] results in 30 µs cycle time for $n=8$ slaves and 32 bit information/slave in a 100 Mbps implementation.

EtherCAT is currently being used in HVDC substations for communication between input/output units and main computers at up to 10 kHz [8].

4 Discussion

During control and protection system design for a substation, first, a communication architecture has to be chosen. Second (and based on the architecture), a communication protocol would be chosen. If a substation within an MTDC system shall be equipped with control and protection equipment of different vendors, this approach is not possible today. Standards for communication architecture do not exist. Therefore, step 1 and, as a result, step 2 cannot be executed. When discussing communication protocols as done here, it has thus to be considered that many aspects are unclear.

However, it is clear that IEC 61850 for AC substations cannot directly be translated into HVDC world. The following aspects should be kept in mind:

- The process bus in a digital DC substation has to be very fast and deterministic in order to distribute measurement values sufficiently quickly and reliably.
- The IEC 61850-9-2-LE profile is most probably too slow for MTDC protection as new samples are published only every 250 µs. However, sampling rates of at least 50 kHz (20 µs) are discussed in the literature. Also, the sampling rate of 96 kHz should be considered, as specified in IEC 61869-9.
- Time synchronisation over a network can be achieved with an accuracy of below 1 µs which is in accordance with IEC 61850. It is not clear today to which extent MTDC protection using communicated measurement signals within a DC substation will require a timestamp.

An architecture where MU and IED are placed in the same physical device might be an option to increase speed as shown in Fig. 5.

A first potential candidate for inter-IED communication in MTDC protection is HSR. HSR provides bumpless recovery in case of communication failure. However, the number of devices in an HSR ring is limited due to bandwidth to six devices when using SV and a 100 Mbps communication link. Therefore, modifications

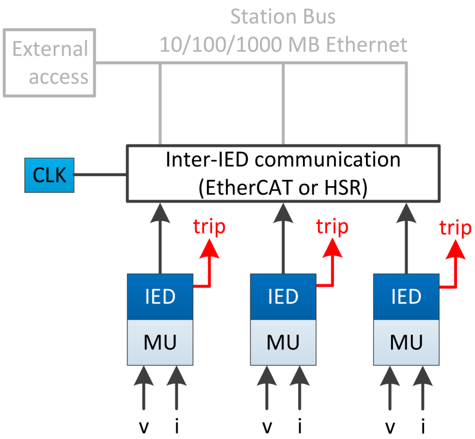

Fig. 5 *Substation architecture with combined MU and IED*

might be necessary to achieve the required speed and data throughput. This is especially the case for DC busbar protection where measurement data from all links is required. Furthermore, the repeated sending of multicast GOOSE messages can lead to high data traffic in the HSR network. A gigabit HSR implementation might be required to achieve the necessary speed and bandwidth for MTDC protection.

A second potential candidate for inter-IED communication in MTDC protection is EtherCAT. EtherCAT is a flexible, redundant and efficient protocol. One EtherCAT frame is large enough to contain measured values and binary information, for example, trip signals. EtherCAT is an efficient protocol because one Ethernet frame is used to exchange data of all slaves in a daisy-chain fashion. In the case of HSR, different types of messages are used to exchange those data such as GOOSE or SV. Furthermore, EtherCAT provides a mechanism for time synchronisation, and, being an open standard, it is favourable for vendor interoperability.

5 Conclusion

Protection of MTDC grids has to be fast in order to achieve safe and reliable operation. When several vendors are involved, the system protection can no longer be executed in one central unit (one central IED), but rather has to be distributed across several IEDs. These IEDs must be able to communicate.

Designing a communication with high speed and large bandwidth is a challenge. It is true that substation communication introduces additional delays; however, these might be negligible compared with the DC breaker opening times which are at least 2 ms. There are no existing standards for digital DC substations. Therefore, the existing AC standards, namely IEC 61850, were discussed here. It was found that the corresponding application note IEC 61850-9-2 LE cannot be applied for MTDC protection without modifications.

A different view on substation architecture with combined MU and IED in one device was proposed here. Two possible solutions for fast and reliable communication between IEDs, namely HSR and EtherCAT, were discussed.

Further work is required with regard to testing the suggested approaches. Ultimately new standards for communication in digital DC substations are required.

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