OPTIMIZED ARCHITECTURES FOR PROCESS BUS WITH IEC61850-9-2

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SUMMARY

IEC 61850, the standard for communication in substations, supports all tasks to be performed in the substation and provides by the process bus option also the link to the primary equipment like switchgear and instrument transformers. It is shown that the standard supports the trends in substation technology like the use of combined and non-conventional instrument transformers. It is discussed how different architectures providing the requested protection zones fulfil the requirements for flexibility, availability and dependency, minimize the number of devices (cost, failure rate) and communication components and facilitate the implementation of the time synchronization needed for samples. How to get with these criteria the optimized process bus architecture is shown on the example of the one-and-a-half breaker substation topology.

KEYWORDS

Substations, Substation Automation, IEC 61850, Process bus, Protection, Control, Voltage Sensor, Current Sensor, Trip, Command, Merging Unit, Process close architectures
1 Introduction
The standard IEC 61850 for communication in substations available since 2005 is increasingly used for Substation Automation (SA) systems. The standard supports interoperability between devices from different suppliers and allows the integration of all in one homogeneous system. The purpose of SA systems is the supervision, operation and protection of the power system and, especially, of the primary technology in the substation. Therefore, the standard has to support also the trends in switchgear and sensor technology including the interface between switchgear and SA. IEC 61850 does it by the so-called process bus which transmits not only commands and position information but also samples (U, I) and trips. Using the process bus raises the question for optimized process near communication architectures.

2 Technology Trends
2.1 Switchgear
Novel integrated multi-functional switchgear with integrated sensors and actuators including monitoring and diagnostics functions have been developed. Nonconventional instrument transformers for current and voltage without the heavy iron core meaning e.g. no saturation are available both for protection and for metering. Common are Rogowski coils for current and capacitive dividers for voltage measurement. The first ones are competed by fiber optic sensors (Faraday Effect), the second ones by electro-optical effects in crystals. The classical drives with spring or pressurized gas energy storage will be competed by motor drives, contacts by optical positions sensors. All these new solutions provide not anymore the classical interface standard of 1/5 A or 110/220 V, include process near electronics and rise questions for a new standards.

The transmission level from 220 kV to 550 kV claims for independent main 1 and main 2 protections. This requirement is covered e.g. by the combined (U, I) sensors from ABB for single-phase GIS with following features:
- One single-phase GIS component containing two independent sets of capacitive sensors for voltage and Rogowski coils for current
- Two independent electronics mounted directly on the primary converter containing signal acquisition and signal processing functions and a serial communication interface

2.2 Substation Automation
The functionality of microprocessor based IEDs (intelligent electronic devices) includes multiple functions for protection, control and monitoring. The exchange of data between IEDs, with the station and network level control systems is performed with serial, interference free communication by fiber optics. This is the basis of SA systems which have been widely introduced in substations but with proprietary communication solutions. The driving force for a communication standard in SA is interoperability between devices of different suppliers to be independent from one supplier and one generation of IEDs. The answer is IEC 61850.

2.3 The standard IEC 61850
The standard IEC 61850 for communication in substations defines a domain specific data model (data and services) supporting all functions in substations [1]. The standard has selected also a main stream communication stack (Ethernet, TCP/IP and MMS) where the data model is mapped to ([2], [4]). Both the control service (services see part 7-2) for operation and the resulting report service is not time critical (order of 1 s). There are two time critical services defined: The GOOSE (generic object oriented system events) service with fast messages (transfer time down to 4 ms for 50 Hz) is focused on information exchange between IEDs like trips, blockings or releases. The SV (sampled value) service is intended mainly for the transmission of synchronized voltage and current samples (mapping to stack [2]). Both time critical services are mapped directly to the link layer of Ethernet. The connection between the IEDs at bay level and at process level are dominated by the time critical services and called Process Bus. Most demanding is the transmission of synchronized samples which needs time synchronization of 1 μs accuracy. For IEC 61850 this synchronization is today performed by PPS pulse [3] on a dedicated wire/fiber but it will be replaced in the future by synchronization over
the Ethernet according to IEEE 1588 [5]. This bus allows common solutions both for the Nonconventional and conventional sensors and actuators. The functions in any protection or control IEDs using the process bus generally do not see any difference.

2.4 Merging Unit and Definition of Sampling Rates

To facilitate easy synchronization and efficient combination at least for limited signal channels the so-called logical merging unit (MU) was introduced (Figure 1) in [3] according to the definition in [7]. According to IEC 61850 the MU contains the Logical Nodes TVTR (voltage transformer) and TCTR (current transformer). It combines related inputs like the currents and voltages from three phases, and additionally also the (calculated or measured) zero currents and voltages in one dataset for transmission with the SV service to all subscribing IEDs. The physical MU (IED) may contain several logical MUs, e.g. three in the use cases discussed below. The inputs may come in principle from all types of instrument transformers. These requirements may result in mixed mode by conventional and non-conventional instrument transformers for bay level IEDs or MUs (see Figure 2).

IEC 61850-9-2 leaves both the combination of signal channels to data sets and the sampling rate as free engineering parameters. To facilitate the application of such samples and reduce acceptance problems, the user convention IEC 61850-9-2LE [3] issued by the UCA International Users Group has recommended values for these parameters at least for the most common applications i.e. using 80 samples per cycle for protection and 256 samples per cycle for power quality.

![Figure 1 - Schematic diagram of a merging unit (MU) with relevant Logical Nodes](image1)

![Figure 2 – Mixed mode with sampling in external MU to the left and local sampling in the bay device to the right in the figure, refer to rule 4](image2)
2.5 The breaker IED

To connect the bay units serially with the switchgear a so-called Breaker IED is needed which picks up all position indications from the breakers by the report service and issues commands by the command service and trips by GOOSE messages to the breakers. This IED is applied like a remote I/O but has to contain at least the Logical Node XCBR (one instance for three pole breakers and three instances for single pole breakers).

3 Use Case

3.1 The one and a half breaker topology

The use case we are considering in this paper is the one and a half breaker topology build in GIS technology. It should be noted that the discussion of a double busbar topology would be similar but less complex. For one and a half breaker topology, implementations with three or six current sensors for protection exist (Figure 3) depending if overlapping protection zones are required or not. The busbar voltage is basically measured outside the diameter.

When this topology is implemented using a combined sensor (U, I) as mentioned in the previous section, additional voltage sensors i.e. one per current sensor are available. As a consequence, with six combined sensors based on current sensors requirements, there is no need anymore for voltage measurement at the busbars.

![Figure 3 - Diameter of one and a half breaker topology with 3 (left) or 6 (right) combined sensors for current and voltage](image)

For the discussion, the following functionality of the protection and control system is assumed (see Figure 4):

- **Line protection** means distance protection which needs not only the line voltage but also the sum of the currents in the two segments feeding the line.
- **Busbar protection** needs information from all current transformers of the segments that feed into the protected busbar.
- The **Control IED** (one per breaker) is considered as host for the Synchrocheck function only needing the voltage on both sides of the breaker. Therefore, the busbar voltage needs to be distributed to all diameters if there are not enough voltage sensors in the diameter as in the case three combined sensors.
• *Revenue metering* is excluded and, therefore, not further discussed.

Normally, a line protection relay requires only information from its own diameter. The exception is the case of parallel lines to compensate for mutual coupling.

![Figure 4](image-url)  
**Figure 4** – Data flow from three combined current and voltage instrument transformers to protection and control IEDs

### 3.2 Optimized synchronization for the required time coherence

All data that is used for calculation (impedance) or comparison (differential) by the protection must be time coherent. This generates a requirement to synchronize the different sources (IEDs) of related data to each other. The time synchronization method used today between different IEDs 1 PPS (1 pulse per second). The future alternative with IEEE 1588 mentioned above will not be discussed in this paper.

For the synchronization or time coherence the following set of general rules is valid:

1. All signals in an IEC61850-9-2LE data set are time coherent since all come from the same logical MU.
2. All data sets from a physical MU are time coherent i.e. the physical MU guarantees the time coherence between the logical MUs it contains.
3. Data sets from different physical MUs are only time coherent if the physical MUs are synchronized.
4. A bay device that uses data from MU and also has local sampling of conventional CT and PT in b

![Figure 5](image-url)  
**Figure 5** – Time correlated output e.g. for point-on-wave switching
The ultimate requirement on the data used by the applications in the bay devices is that it shall be time coherent. The often used term synchronization can be misleading in the sense that it suggests a central clock that distributes time information to all bay devices. Although this may be required for some applications like time tagging of events (1 ms), it is not a requirement for the sampled analogue samples. An optimized scenario to achieve the required time coherence may be realized by the following rules:

1. Synchronize two MUs directly with a connection between the MUs. This may be required for parallel line compensation where the synchronization is between two independent MUs in the two bays. It may also be required for busbar voltage distribution where the distribution of time information is provided from the MU of the busbar voltage to all bays requiring the use of this voltage.

2. Synchronize from the MU directly the bay device when the bay device has a local sampling of conventional CT and VT to be synchronized with the data of the MU or when the output must be time correlated to the sampled input data.

3. Synchronize from the MU in each bay the busbar protection (Figure 6) above. This allows for re-sampling of the data from all bays to a common time base in the busbar protection. This will require different topologies for the 1 PPS depending on if a centralized or decentralized busbar protection scheme is used. It will support also mixed mode with local sampling in the busbar protection.

Figure 6 – Data from several MUs without common time base are time correlated through the re-sampling (example Busbar Protection BBP)

Figure 7 – Synchronization of bay device by MU (left) and one MU by another one (right)
In order to realize the above scenario the MU, Protection and control devices must comply with the below requirements:

1. The physical MU shall contain more than one logical MU. This removes much of the need for external synchronization.

2. The MU shall be capable of sending as well as receiving 1 PPS time synchronization information. This removes the need for additional centralized or distributed clocks or time sources.

3. The protection and control devices shall be able to receive 1 PPS time synchronization information. This allows for local sampling of conventional CT and VT as well as to time correlate output data to the sampled input data from the MU.

4. Busbar protection shall be able to receive 1PPS time synchronization information from each bay and re-sample the data from each bay with the internal clock.

Following these rules we have eliminated the need for a central clock, reduced both the external synchronization links and the number of devices required to achieve the time coherence to a minimum. Final remark to time synchronization is that it is anticipated that the 1 PPS will be replaced in some future by the IEEE 1588 [5] as general method for high accuracy time synchronization in IEC 61850 networks.

Note: Any loss of time synchronization between IEDs has to result in a fail safe state producing a dedicated failure report and a continued operation with the local clock as long as acceptable by the function to be performed. The loss shall not interfere with tasks which do not need synchronization.

3.3 Towards an optimized process bus architecture

For the process architectures 3 or 6 combined (U, I) sensors per diameter of the One and a half breaker topology are considered. Only one of the two redundant protection systems (main 1 and main 2) has to be considered. The sensors are fully redundant but all other devices must be seen per protection system.

The first architecture (Figure 8) has one MU for each group of three sensors (one group for each phase measuring both voltage and current). The sampled data is sent from the MU with IEC 61850-9-2LE via switches to the protection and control devices. The physical MU here needs only one logical MU and one physical output.

The second architecture (Figure 9) has two MUs per diameter, i.e. one per line. Each MU can receive and synchronize input data from several groups of sensors. For the implementation with three combined (U, I) sensors, the raw signals from the busbar voltage sensors are distributed via splitters over optical fibers to all diameters. Each MU provides several IEC 61850-9-2LE outputs eliminating the need for external switches.

In the third architecture (Figure 10) there is only one MU per diameter i.e. one per two lines. The MU has to have enough inputs to receive the data from all groups of sensor in the diameter and also from the busbar voltages in case of three combined (U, I) sensors. Each MU provides several IEC 61850-9-2LE outputs, more than in the second architecture, in order to eliminate the need for external switches.

The criteria for the comparison of different architectures are the number of devices (switches, MU), the requirement for synchronization of the MU, the busbar voltage distribution, protection schemes and dependencies between the bays in the diameter. The characteristics are listed in Table 1. Comments to the table:

1) This dependency can be removed by using two switches in the diameter, one per each bay. This will however, in addition to the need for the extra switch, also require two outputs from the MU for the middle sensors in the diameter and more connections to the busbar voltage switch.

2) The extra switch or splitter is required since the busbar voltages need to be distributed to several diameters.
Figure 8 – Three (left) or six (right) combined sensors per diameter, voltage instrument transformers (left) at the busbars, with one merging unit (MU) each.

Figure 9 - Three (left) or 6 (right) combined sensors per diameter, voltage instrument transformers (left) at the busbars, with one merging unit (MU) per line.
Figure 10 - Three (left) or six (right) combined sensors per diameter, voltage instrument transformers (left) at the busbars, with one merging unit (MU) per diameter.

3.4 The criteria for the evaluation

Number of devices:
Less devices is positive for cost as well as availability, for the MU we use this criteria as well but it must be seen in the light of that each sensor has its own signal processing and the MU is additional to this.

Synchronization:
Less need for external synchronization is positive and the reduction of this can be achieved by including several sensor groups in one MU.

Dependency:
No dependency between the bays in the diameter is positive since it allows for independent maintenance of the MU. This can be argued to be achieved already for the protection since there are redundant protection systems. It is kept here though due to the value of having the redundant protection intact for the bay that is not concerned.

Busbar voltage:
No need for the distribution of the voltage is positive, distribution via splitter is acceptable and distribution via external switch is deemed negative due to extra equipment required.

The results are summarized in Table 2.
Table 1 – Characteristic features of process bus architectures for use case

<table>
<thead>
<tr>
<th>3 NCIT per diameter (to the left in Figures 4 to 6)</th>
<th>6 NCIT per diameter (to the right in Figures 4 to 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non overlapping protection zones and no T-tone protection</td>
<td>Overlapping protection zones but no T-tone protection</td>
</tr>
<tr>
<td>- External switch in diameter</td>
<td>- External switch in diameter</td>
</tr>
<tr>
<td>- One MU per sensor</td>
<td>- One MU per sensor</td>
</tr>
<tr>
<td>- Extra switch for distribution of busbar voltage</td>
<td>- Many MU must be synchronized externally</td>
</tr>
<tr>
<td>- Dependencies between the two bays via the common switch</td>
<td>- Distribution of busbar voltages via splitter, no external synchronization required</td>
</tr>
<tr>
<td>+ flexible solution that decouples the signal distribution (communication network) from the functionality</td>
<td>- Two outputs directly or via splitter from mid sensor is required</td>
</tr>
<tr>
<td>+ No external switch</td>
<td>+ No external switch</td>
</tr>
<tr>
<td>+ One MU per bay</td>
<td>+ One MU per bay</td>
</tr>
<tr>
<td>+ No external synchronization required</td>
<td>+ No external synchronization required</td>
</tr>
<tr>
<td>+ No dependencies between the two bays</td>
<td>+ No dependencies between the two bays</td>
</tr>
</tbody>
</table>

Table 2 – Evaluation table of process bus architectures for use case

<table>
<thead>
<tr>
<th>3 NCIT per diameter</th>
<th>6 NCIT per diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MU per NCIT (Figure 10)</td>
<td>1 MU per line (Figure 11)</td>
</tr>
<tr>
<td>-5</td>
<td>+3, -1, 0</td>
</tr>
<tr>
<td>-5</td>
<td>+4, 0</td>
</tr>
</tbody>
</table>

Summing up the plus and minus for the architectures we see that the architecture with one MU per line i.e. two per diameter gives the optimal solution for both sensor implementations. The implementation with 3 combined (U, I) sensors per diameter has generally no benefit compare with 6 ones due to the penalty we put on the extra output from the middle sensors in the diameter needed for the two MUs per diameter.

The busbar protection data transmission we can see as a duplication of the connection we have for the P1L and P2L in the Figure 10 for the case with 2 MU per diameter. In the case with 1 MU per combined (U, I) sensor as well as with 1 MU per diameter, the connection can be reduced to one link per diameter for the data transmission. However since the busbar protection may not always be redundant the criteria for the independency between the bays will be in favor for the architecture with
For the busbar protection a distributed approach will allow for less process bus cabling for the data transmission as well as time synchronization.

For all cases above the addition of a combined (U, I) sensor in the line will allow to measure the current for the line protection directly and facilitate T-zone protection. The sensor in the line will be necessary if there is a requirement for revenue metering. In this case the sensor data can be used also for the line protection.

4 Conclusions

By an appropriate design and size of MU as well as of bay devices an optimized architecture for the process bus is possible, where the need for external synchronization as well as external switches can be almost eliminated. In the cases where it is still required the building of synchronous islands instead of a centralized and complete synchronization of all devices increases availability and reduces cost.

The choice of two MUs per diameter is optimal with respect to the amount of devices and independent maintenance of the bays for both implementations with three or six combined (U, I) sensors per diameter. Also for the busbar protection this is the optimal architecture with respect to the independent maintenance of the two line bays of the diameter.

With the future use of IEEE 1588 replacing the 1 PPS this architecture may be further improved but this remains an open topic for further investigations.

BIBLIOGRAPHY

[1] Data model and services (IEC 61850-7-1, 7-2, 7-3, 7-4, www.iec.ch)
[7] IEC 60044 Instrument transformers