21, rue d'Artois, F-75008 Paris
http://www.cigre.org

B5-103

Session 2004

DESIGN OF IEC 61850 BASED SUBSTATION AUTOMATION SYSTEMS ACCORDING TO CUSTOMER REQUIREMENTS

K.P. BRAND*, C. BRUNNER, W. WIMMER
ABB Switzerland Ltd, Baden and Zürich

(Switzerland)

1 INTRODUCTION

The standard IEC 61850 „Communication Networks and Systems in Substations“ will provide interoperability between the electronic devices (IEDs) for protection, monitoring, metering, control and automation in substations. Interoperability and free allocation of functions opens up a vast range of possible solutions, but the consideration of customer requirements and commercially available equipment will scale down this range to a handful of them. It is important both for utilities and Substation Automation system providers to understand this process. This design process will be outlined in the following chapters.

2 THE IMPACT OF IEC 61850 ON SUBSTATION AUTOMATION

The basic *functionality* of Substation Automation is given by its tasks and will not be changed by IEC 61850. On a first look, also the system architecture is not so much changed. Nevertheless, *communication* is the backbone of SA and, therefore, IEC 61850 the most important key for designing systems. A lot of inherent features in IEC 61850 like the use of object oriented data model, the selection of mainstream communication technology allow responding very dedicated to requirements stated in *customer specifications* not by chance but based on standardized rules. Therefore, these features support designing optimized systems. *Optimization* includes not only functional performance but also economic aspects like investment, availability, expandability and maintainability, i.e. all life cycle costs. For specification, design and engineering, the most important feature of IEC 61850 is its support to strong formal description of the substation and its automation system. The use of this strong description facility will be mentioned in all steps below if applicable. If the *customer* is not providing this formal specification, this task is left for the *system integrator* or *provider* to use its power for the SA system design.

---

* klaus-peter.brand@ch.abb.com

3 CUSTOMER SPECIFICATION

3.1 General

The customer specification has to include three areas of requirements, i.e. the functionality needed, the performance requested, and all constraints applicable. The *functionality* refers mainly to the given single-line diagram of the substation and the protection and control functions of the substation automation system. The *performance* includes not only the reaction times on certain events but also figures for reliability and availability. The *constraints* may include but are not restricted to given switchgear (process) interfaces, to interfaces needed for remote network control centers or remote maintenance systems. Constraints include also the geographical situation on-site, i.e. the distances between components, building space, shielding and grounding facilities, and last not least the existence of prescribed IED types. There might be non-technical constraints like requested quality certificates, preferred project management procedures, documentation needs and training requirements etc. The last ones are, however, outside the scope of this paper.

3.2 The Single Line Diagram

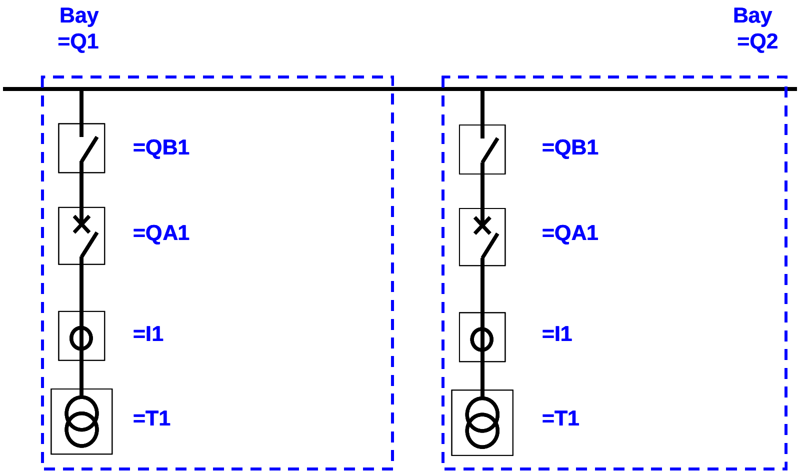

Figure 1 – Part of a substation single line diagram (example) with equipment designations

As an example, part of a single line diagram (SLD) of a substation with two transformer bays is shown in Figure 1. The minimal needed automation of this substation part and the intended operating procedures already contain implicitly a big part of the functional specification. The SLD shows all power equipment to be controlled and protected, and defines how this shall be done from the operator's point of view. The topology, how the power equipment is electrically connected, gives further information needed e.g. for interlocking and synchrocheck functionality. The equipment designation [1] in the SLD gives further inputs for detail engineering of the SA systems. The SLD as part of the specification is currently drawn on paper. The XML based Substation Configuration description Language (SCL) of IEC 61850 [2] offers a formal way to describe the SLD. Passing the SLD in this form as file reduces misunderstandings and enables automatic processing of it without new data entry.

3.3 Functions

3.3.1 Specification method

The functionality as given by the SLD has to be, however, further refined. All requested functionality should be specified without reference to any implementation to allow optimizing the solution. Only by this approach, the system design can exploit all benefits of state-of-the-art technology. Up to now, the most formal and simple way is to add the Device Function Numbers according to IEEE [3] if applicable. IEC 61850 offers the concept of *logical nodes* (LN) for formally defining functions. The LN is the smallest part of a function, which communicates with other LNs and which may be implemented in a separate IED. The LN is an object, which comprises at least all related mandatory data and attributes and all extensions according to the rules of IEC 61850. It defines also the standardized access to its data. Therefore, LNs allow defining functional requirements in a standardized way. The resulting LN names (see section 3.3.2) may be used in the SLD (see Figure 2) representing the requested functionality. By adding the data objects used by the LNs as LN type

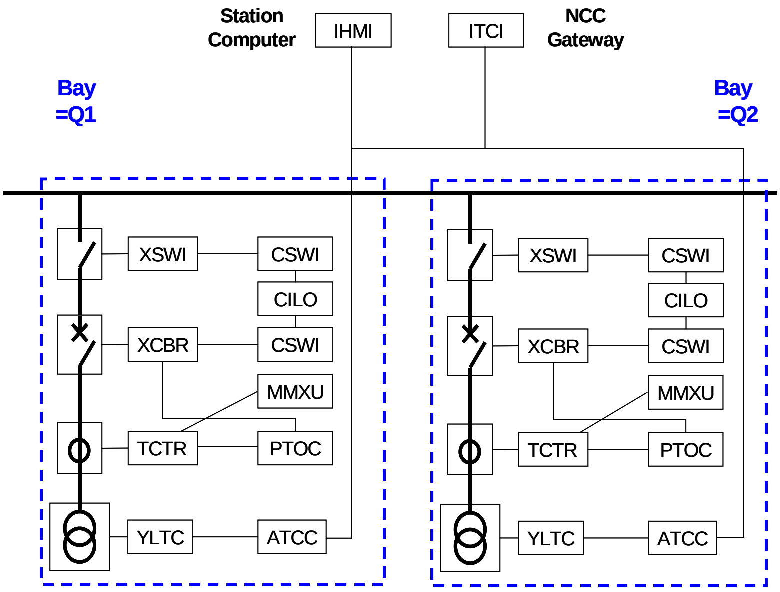

Figure 2 - Part of a substation single line (example) with function allocation by LN names

definitions, this specification will contain also the data as described by the well-known signal lists. At this level of design, no allocation of functions to IEDs is done.

Specifying according to IEC 61850 means that the interconnection of the functions is described also. To give signals, functions and connections the proper meaning, we have to know which power equipment and bay within the switchyard refers to what function or reverse. This may be done with help of SCL. The resulting file is called System Specification Description (SSD) file. However, this SSD file doesnot define specific details of function implementation and function interaction. These must be described as today with text blocks and diagrams. The SSD file allows however including short text parts or references to files containing additional information into the objects of the SLD as well as into the LN definitions. With these features the degree of understandability is enhanced quite a lot compared to current verbal specification, and supports automated consistency checks of quotations against specifications.

3.3.2 LNs used in the example

For better understandability of the figures, the LN class definitions according to IEC 61850 are given: XCBR *Circuit breaker*, XSWI *Isolator or earthing switch*, TCTR *Instrument transformer/transducer for current*, YLTC *Power transformer*, CSWI *Switch control*, CILO *Interlocking*, MMXU *Measuring unit*, PTOC *Time overcurrent protection*, ATCC *Automatic tap changer control*, ITCI *Telecontrol interface or gateway*, IHMI *Human machine interface, operators place*.

3.4 Performance

Performance comprises a wide range of topics such as response time, safety and reliability. These requirements guide the allocation of LNs and their related functions to devices, and strongly influence the structure of the communication system. *Response time* requirements can be subdivided into average response time requirements, which are not process critical, and absolute worst case requirements, whose deviation might lead to dangerous process states. If the performance requirements are safety related or not, depends on the function using this data. Therefore, they should be specified per function. For *safety* it might be sufficient to specify the degree of safety to be met as a safety probability per function, typically a failure probability of 10^{-5}/h to 10^{-6} /h for protection related functions.

It is up to the system designer selecting IEDs, communication configurations and function implementations which match these response times and failure modes additionally to the needed availability. Some considerations in the context of IEC 61850 can be found in [4], [5] and [6]. This approach is, however, only possible if the communication system is not already fixed. In this case the communication system designer has the responsibility for the safety of distributed functions.

Safety and availability are normally specified as probability values, together with some general rules like “no single failure shall endanger the safety" or "... shall lead to function loss”, etc. The probability numbers can either be derived by comparison with conventional systems offering sufficient safety and availability, or by considering the costs of failures. Some explanations on availability calculations and an example to the last case can be found in [7]. The question has to be addressed also what kind of redundancy results from the *reliability* requirements.

3.5 Constraints

The constraints include some boundary conditions like the geographical extension and topology of the substation, the existence of building structures, switchyard kiosks, shielded rooms for the station HMI, etc. All these conditions influence the SA system architecture regarding possible IED locations and the resulting communication links. Other boundary conditions are the interfaces to auxiliary power supply system, the switchgear and to network control centers. Especially, the type of process interface (parallel wired or serially linked) can vary as boundary for a system provider depending how the delivery is organized and allocated to different providers. Devices already existing or prescribed by the customer may be also constraints in the specification, but are neglected in the context of this paper. Given redundancy like main 1 and main 2 for protection independent from the considerations in section 3.4 may appear as constraints in addition. The *performance* requirements together with the given *constraints* define the final *physical architecture*.

4 THE DESIGN PROCESS

4.1 Design steps

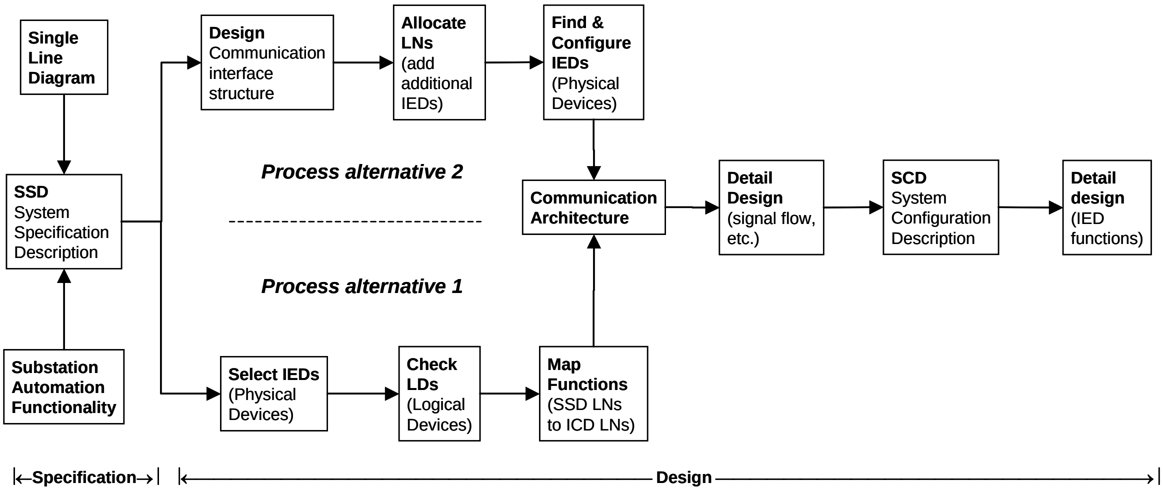

Figure 3 – Steps of the design process (process alternatives described in the text)

The general design process from customer specification to final system design is principally independent from any standard but some features of IEC 61850 influence and facilitate this process.

4.2 Start

The design process can either start with the functional specification, in case of IEC 61850 preferably with an SSD description, or with the boundary conditions (see Figure 3). When starting with the *functional specification*, the next step is to search for IEDs, which support the required functions. Then it has to be checked if the grouping of functions (LNs) on the found IEDs fulfills the availability and safety criteria. In the next step the boundary conditions and the availability conditions are used to design the connecting communication architecture in a cost optimal way. Now the overall system structure is known, and detail design can start. This kind of approach is mostly used if the types of available IEDs are well known, have relatively static configuration range, and are not too large.

When starting with the *constraints* and *performance requirements*, this determines the minimum number of IEDs needed at the interface locations, and their main functionality. This first design step must already cover the requirements for functional redundancy (e.g. demanded main 1 and main 2 protection). Based on this and the required functionality the interfacing IEDs are determined, and which functions are available on them. If not all required functionality is covered, further IEDs have to be added. Finally the connecting communication architecture is designed in a cost optimal way. This kind of approach is mostly used if a large number of IED types (possibly from several manufacturers) are available, or IEDs can be flexibly configured.

4.3 *Tools and formal specification*

To get maximum benefit from tool support the *specification* has to be translated into the SCL based SSD (System Specification Description). The SSD has to be complemented with more detailed specification where needed. The SSD is an *unambiguous input,* which enhances the quality of the specification and allows functional simulation to see the interaction of LNs and to get a base for estimation of communication load, performance, completeness, etc. before the system exists.

4.4 *Grouping LNs to LDs and non-functional requirements*

For both approaches outlined in section 4.2, we have to decide the geographical allocation of functions. If we start with given IEDs, the IEDs have to be allocated to these functions. During this allocation we have to prove that no constraints are violated and the reliability and availability goals are met. If we have a free choice of devices, we may first group functions, i.e. the LNs belonging together, in Logical Devices (LD). The next step is combining all LDs in IEDs in such a way that a minimum number of devices results but all constraints are fulfilled. Finally, we have to find proper devices for implementing this optimized solution. The device selection may be an iterative process for both approaches.

4.5 *Example for Selection of IEDs and Allocation of Functions*

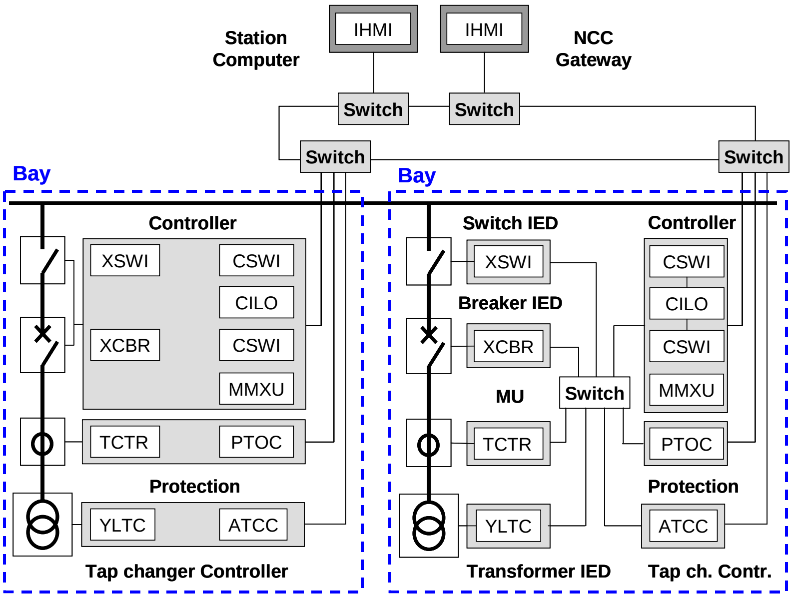

Figure 4 - Single line with allocated IEDs without (left) and with process bus.

In case of free selection of IEDs, the availability requirements, at least for transmission substations, end up mostly with *two devices* per bay. If there are prescribed device types with allocated functionality, the number may be higher. In addition, the selection is influenced by the process interface normally given by the switchgear. Figure 4 shows examples for both conventional hardwired interfaces in the bay IEDs and remote interfaces near the switchgear connected to the bay IEDs by the process bus. The IED allocated to the instrument transformers TCTR is called Merging Unit (*MU*) since it may merge the signals e.g. from all the three phases or from all currents and voltages of one line or one diameter and provide it as sampled analog values (SAV) according to IEC 61850-9-x. *Switch*es are active communication nodes connecting Ethernet links.

4.6 *The requirement of redundant protection*

Either the reliability calculations or given constraints may request main 1 and main 2 for protection. The example in Figure 4 does not cover this case. To avoid single point of failures, there have to be two process bus segments, which connect the sensor (Merging Unit IED, i.e. MU) with the protection and breaker (Breaker IED) each (see Figure 5). Each segment may contain an external or embedded switch. If any component of one segment fails, the protection of only this segment is out of order, and at least the other one is operating well. Like in section 4.5 the availability requires two *process-near networks* meaning two independent switches per bay. Control may be connected to any of the two switches. If the controller has two outputs it may be connected also to both switches increasing the availability of the control channel. The connection of both protections with both switches brings only an improvement if all four components (MU, Breaker IED, Protection, Switch IED) have roughly the same availability.

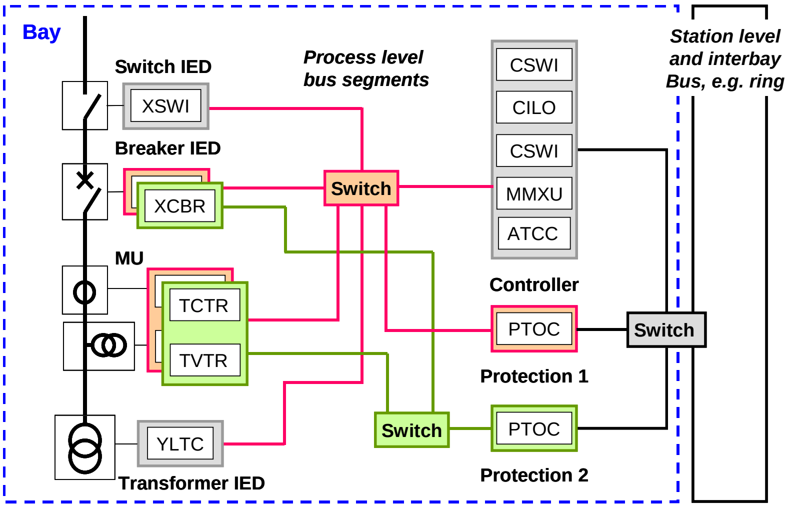

Figure 5 - The process interface with redundant protection

4.7 The formal description of IEDs

The standard IEC 61850 requires that any conformant IED has to provide an SCL based description, i.e. a file with all its capabilities. This IED Configuration Description (ICD) may be supplied on data storage medium like a CD or may be readable from the device itself. Important is that this standardized file can be read and written by all conformant system engineering tools. This tool may also contain a database with all ICDs for IEDs, which are common for the system integrator.

4.8 Detail engineering

The result of the design process for IEC 61850 based systems can formally be described in an SCD (System Configuration Description) file, which contains the logical communication connections between IEDs within subnetworks and routers between subnetworks. The detail engineering on system level has to determine the communication addresses and the detailed data flow between the IEDs in terms of data sets and signal inputs to clients. This signal-level data flow engineering replaces to a big extent the engineering of the conventional wiring. Due to the inherent semantics of the IEC 61850 data model, this step can also be supported with object based or even automated signal engineering [8]. The resulting SCD file contains individualized IED descriptions for the system under design. These descriptions have to be downloaded via the IED tools to the IEDs to make them aware of their place in the system and their connections to other IEDs.

4.9 Communication topology

Logically, communication according to IEC 61850 takes place between LNs. In any implementation, physical communication takes place between IEDs. Multiple communication ports may exist. IEC 61850 is based on Ethernet, and Ethernet allows different physical variants. Since the standard and Ethernet is supporting both client-server relations and peer-to-peer communication, any communication topology connecting all related IEDs fulfills the functional requirements. Therefore, the final determination of the communication topology is strongly influenced by constraints, i.e. by non-functional requirements like performance (section 3.4), availability and others (section 3.5).

4.10 The final system

The selected IEDs together with the communication architecture represent the final system. Different solutions are possible. Since all solutions have their functional and non-functional properties and their price tag, a proper trade-off can be made. Having the complete formal description of the system and all additional information needed, this evaluation can be made before any piece of equipment is ordered, e.g. already in the quotation phase. In case of ordering, the high level data and communication engineering is already made. However, IED detail engineering like configuration, parameterization, process interface and human interface engineering still must be performed.

Two extreme examples are given in what follows. They include all essential functions from the station level with its station computer and gateway to the network control center down to the process level with conventional and unconventional sensors and actuators, i.e. station bus and process bus features. According to the scope of IEC 61850, details of functions are not discussed but all related communication aspects.

4.10.1 MV system (Example)

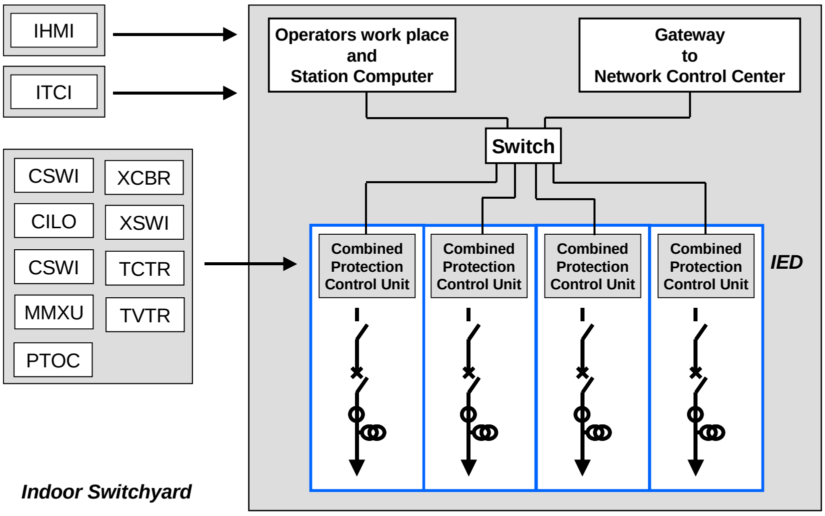

Figure 6 - Compact Substation Automation System for a MV substation

Functional requirements are given according to section 3.3 with no redundant bay protection. The following *non-functional requirements* apply: Determined hard-wired process interface, switchgear cubicles at one place, prescribed combined protection-control units, average system availability, indoor switchyard with no separated control room. The *result* is a SA system with protection independent from any serial communication but with a single point of failure for the control and information exchange from station level and from remote (see Figure 6). With one switch only and one fiber link per bay, the communication system has a low price tag.

4.10.2 HV system (Example)

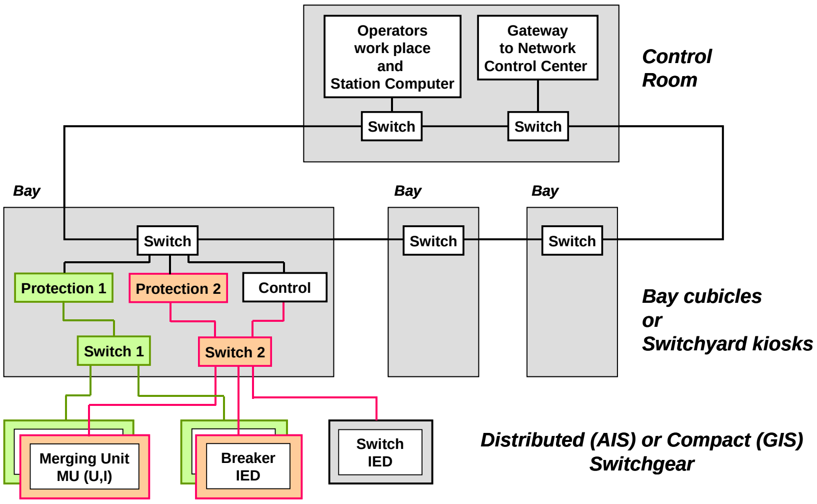

Figure 7 – Distributed Substation Automation System for a HV substation

Functional requirements are given according to section 3.3 with redundant bay protection (main1 and main 2). The following *non-functional requirements* apply: Determined non-conventional instrument transformers (NCIT) with serial interface via Merging Unit (MU), geographically distributed switchgear (AIS), switchyard kiosks, and high system availability. The process near communication fulfills the requirements for main 1 and main 2 protections according to Figure 5. The communication ring is safe against a single point of failure. With one switch for the operators' place, the NCC gateway and any bay, the communication at station level has a high price tag. As seen in Figure 7, the resulting solution may be applied for GIS also. The LNs allocated to the devices are found in Figure 5.

5 CONCLUSIONS

The design process with IEC 61850 is very similar to the common one. It depends partly on the given prerequisites represented by topology constraints or predetermined devices. Nevertheless, based on the inherent properties of IEC 61850, optimized Substation Automation systems can be designed, which are not expensive and un-maintainable singular solutions, but reliable systems based on a global, future-proof standard. The communication system has been proven to be scalable supporting the requested availability. It was also shown that the availability is not only a communication issue but also a matter of redundant functions in separated IEDs.

The free allocation of functions has been used in a very conservative way only. More freedom based both on state-of-the-art in technology and acceptance by the utilities will improve the optimization supported by IEC 61850, but ever existing constraints will always control the process as described in this paper above.

6 REFERENCES

[1] IEC 61346 Industrial systems, installations and equipment and industrial products – Structuring principles and reference designations (http://www.iec.ch)

[2] IEC 61850-6 Communication Networks and Systems in Substations – Part 6: Substation Configuration Description Language for communication in electrical substations related to IEDs (http://www.iec.ch)

[3] IEEE Std C37.2-1996 Electric Power System Device Function Numbers and Contact Designation

[4] Klaus-Peter Brand, Martin Ostertag, Wolfgang Wimmer: Safety related distributed functions in Substations and the standard IEC 61850, IEEE BPT Bologna 2003

[5] Lars Andersson, Christoph Brunner, Fred Engler: Substation Automation based on IEC 61850 with new process-close Technologies, IEEE BPT Bologna 2003

[6] Christoph Brunner, Thomas Kern, Bas Kruimer, George Schimmel, Karlheinz Schwarz: IEC 61850 based digital communication as interface to the primary equipment – Evaluation of system architecture and real time behavior; CIGRE 2004, Study committee B3

[7] Klaus-Peter Brand, Volker Lohmann, Wolfgang Wimmer, Substation Automation Handbook, Utility Automation Consulting Lohmann 2003 (http://www.uac.ch), ISBN 3-85758-951-5

[8] EPA 1191662, Configuration of a control system of an electrical installation, ABB Power Automation AG, 2002