Offprint of article published in PAC World, March 2010

Systems' Reliability and Maintainability

by Dr. Wolfgang Wimmer, ABB, Switzerland

Systems' Reliability and Maintainability

The Impact of Topology awareness

IEC 61850 has introduced a uniform way for substation automation devices to communicate with each other. This together with a bay oriented structure of the automation system leads to implementing previously wired system functions by communicating IEDs in a distributed way. However, just putting the wired connections as signals into serial telegrams still leaves a high complexity in engineering.

Dr. Wolfgang Wimmer works for ABB Switzerland in Baden. He is Principal Engineer in the development of substation automation systems. Wolfgang has a Master of Science degree as well as a Ph.D. in Computer Science from the University of Hamburg.
After some years of developing Computer networks at the German Electron Synchrotron DESY in Hamburg Wolfgang Wimmer made a change. He went to work for ABB for the development of train control systems, later Network Control Systems.
Wolfgang has more than 20 years of experience with development of substation automation systems.
Wolfgang is a member of IEC TC57 WG 19 and WG 10. He is also an editor of IEC 61850-6.
He has written many papers at conferences worldwide.
In his leisure time, Wolfgang likes walking in the mountains as well as along the rivers. He enjoys reading popular books about biology, especially neuroscience, as well as science fiction books.
He also enjoys listening to country music.

It leads also to the increasing dependence of a function in one IED from the data provided by other IEDs, thus introducing some new issues in system maintainability and reliability. Some of these issues can be overcome by a systematically used approach of topology aware functions. This is illustrated by means of some protection related system functions like breaker failure protection, reverse blocking and the lockout function.

Topology aware functions

In the context of this article we call a function 'topology aware' if it either can analyze switch yard related topology properties or use these properties for its application purpose. An example is the breaker failure protection. In case that the operation to trip a breaker has finally failed, it has to trip all breakers in the adjacent protection zones. Thus it must 'know' at least the adjacent protection zones, possibly also the contained breakers – this depends on the details of the function implementation. The distributed functional elements of the breaker failure function, in IEC 61850 terms the logical nodes forming the function, are called 'topology aware', if they 'know' to which protection zone they belong, thus directly understanding what a 'tripping of the zone' means. To get this knowledge, additionally to the wanted function itself a topology analysis function is needed, which tells the application logical nodes to which zone they currently belong. For breaker failure detection the breakers learn to which protection zone they belong. Just sending a trip for an identified zone is then sufficient to trip all breakers contained in that zone. The result of the zone analysis can be shared between different functions relying on the zone concept.

Protection zones are one possible topology part which is useful to identify, especially in the context of protection functions. Other meaningful topology parts might be electrically connected parts with their properties like electrical potential, used for interlocking functions, or defining which healthy VT measures the voltage within a connected part for a bus bar image function.

The following example illustrates the underlying concepts by means of protection zones.

Protection zones

A protection function protects power system objects like lines, transformers or bus bars. A fault on an object is cleared by opening all circuit breakers surrounding it. A part of a switch yard limited by open or closed breakers, which might be dynamically adapted by switching of disconnectors, is called a 'protection zone'. Figure 1 illustrates the zones at a transformer and a bus bar by means of different colors.

In case that one of the breakers fails the breaker failure protection is sending the trip to the circuit breakers of the neighbouring zones i.e. to the protection zones connected left or right of the failed circuit breaker. A circuit breaker belongs to two protection zones, one at each side. The relation between circuit breakers and protection zones depends on the single line diagram and may be very complex, depending on the switchyard single line diagram. Observe that also the overhead line between substations is in this sense a protection zone, just one between several substations. This illustrates that topology aware functions might even extend across several substations, possibly the whole power network.

Using protection zone identity

The protection zone analysis function determines to which protection zones the left and right sides of a breaker belong. In case of a simple topology like 1 ½ breaker, ring schemes or a single bus bar as shown in Figure 1, this can be done statically at engineering time. For more complex multi bus bar configurations this needs to be calculated dynamically. Each zone gets a unique integer as its identification in Figure 1 - the blue zone 1, the green zone 2, the red zone 3, the yellow zone 4.

Topology aware automation functions enhance system reliability and maintainability.

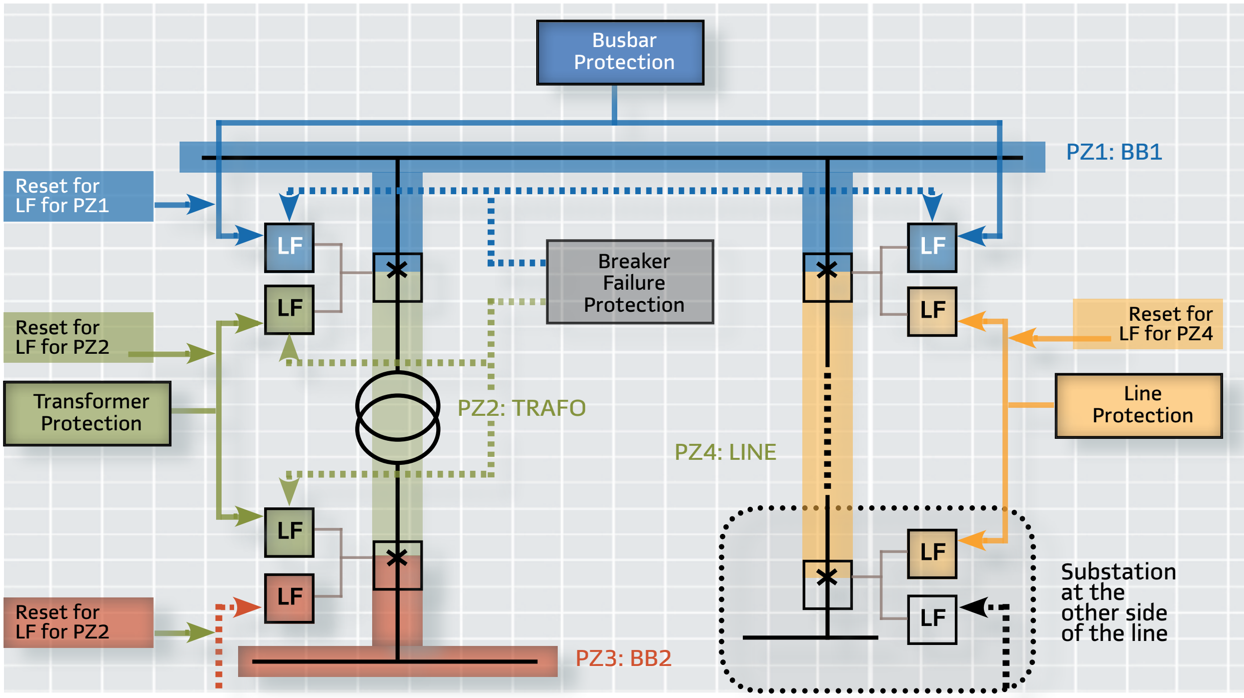
With this identification each circuit breaker 'knows' its two adjacent zones. If now the breaker failure protection has to work for a failed circuit breaker between zone 1 (blue) and zone 2 (green), it just sends a trip for these two zones to the communication system, and all circuit breakers belonging to the zones will trip.

This zone based addressing of the trip commands will drastically reduce the engineering effort for any logic at the circuit breakers for the incoming trip signals, thus making the destination logic independent from the logic at the source IEDs.

The introduction of the IEC 61850 GOOSE service allows:

Implementing time critical horizontally distributed applications like breaker failure protection, lockout, reverse blocking or interlocking by means of serial telegrams instead of cable wiring.

1 Protection zone example - Breaker failure and Lockout function



by Dr. Wolfgang Wimmer, ABB, Switzerland

Calculating topology properties

The main property of a topology part is its identification. For a lot of functions knowing this identification is sufficient. Like already mentioned, for protection zones and simple topologies like 1 ½ breaker or ring schemes or a single bus bar as shown in Figure 1, this can be done statically at engineering time. For multi bus bar systems or other topology part concepts, electrically connected parts, this should be calculated dynamically. But even for the simple systems a dynamic calculation might be advantageous. It allows determining without additional logic, if a circuit breaker is currently connected to a zone, or instead disconnected for maintenance work. Further, if it is known that a closed circuit breaker is not allowed to be tripped due to insufficient energy, the zones can be connected already at zone calculation time leading to a faster breaker failure function.

Another advantage of dynamic calculation is that it can determine common attributes of a topology part together with the topology part identity calculation, i.e. without needing an additional message exchange in case of a distributed implementation. Necessary properties other than the zone identification are application function dependent, although some might be used by several applications. Some examples are discussed later. Determination of topology parts requires knowledge about the static topology of the single line diagram as well as in many cases of the dynamic state of the switches, especially in the case of the protection zones of the disconnectors.

If we assume a fully engineered IEC 61850 system, then the SCD file contains the single line topology and at each switch also a reference to the logical node providing the switch position. This single line description is done in terms of conducting equipment like switches, transformers, VTs and CTs, which are connected to so called 'connectivity nodes'. Connectivity nodes typically stand for an electrically connecting part of the switch yard like a bus bar segment. For better online usage of the topology this formal description should be converted into another one using integers as unique identifications of the connectivity nodes as follows.

Online topology representation: The static switch yard topology is described and can be held in the IEDs as follows:

> The IEC 61850 SCD file contains the single line topology.

- Each connectivity node (CN), i.e. each electrically connecting node like a bus bar segment or the conductive part between switches, VTs and CTs, gets a unique number
- Each conducting equipment references the connectivity nodes to which it is connected by using this number

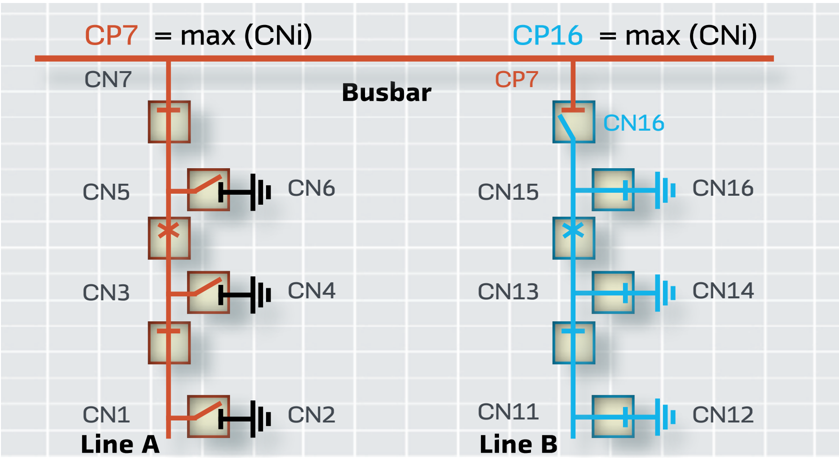
Thus switches, transformers and CTs have typically two CN references, while a VT only has one. If we look at Figure 2, then the circuit breaker between CN3 and CN5 will reference exactly these two CNs. This defines the static topology of the single line diagram, which can be reused by different topology analysis algorithms to identify different kinds of connected parts. Having the topology references only from the equipment to the connectivity nodes (CN), especially the busbar nodes, allows for easy extension of the single line diagram. When adding a new bay to the switch yard, it just has to reference at its busbar disconnectors the existing busbar nodes to which they are physically connected (Figure 2-CN7). The existing part of the system stays unchanged. This feature allows an easy extension of a SA system concerning station related but topology aware functions, if it is implemented in a bay oriented way: any new bay IED needs to reference the bus bar nodes to which it shall be connected application wise.

To hold the dynamic topology, for each kind of topology analysis each connectivity node is assigned to a connectivity part (CP) with a calculated CP number, and also each CN reference at an equipment is additionally assigned to such a CP number, telling for an open switch, to which connectivity part it is connected with its right terminal,

> As a result of the topology analysis for electrically connected parts, the right and left CP numbers of an open switch are identical only if they are connected by a closed loop.

2 Topology example

Connectivity node identifications and two connected parts



and to which connectivity part with its left terminal (Figure 2).

There are different ways to get a common CP identifier. Here the maximum number of all connectivity node numbers in the connected part is suggested as calculation method. As any connectivity node only belongs to exactly one CP, the maximum is unique for all CPs. At initialisation time each CP identification at a conductive equipment is set to the referenced CN number, the CP identification of a connectivity node to its own identification. This gives a consistent CP identification in case that all switches are open. If a closed switch is considered to be a CP connection, it forwards the maximum CP number of its two terminals to the connectivity node at that side with the currently lower CP number, which then adapts its CP identification accordingly and broadcasts it to all other connected conductive equipment.

An example is given in Figure 2. The connectivity nodes are indicated with CN and their identification number. The switch states lead to two connected parts (CP). Within CP7 the highest CN number is 7 at the bus bar itself, within CP16 the highest CN number is 16 at the CN below the bus bar disconnector. The two parts are separated at the bus bar disconnector of Line B, which has CP7 at one side and CP16 at the other side. As a result of the topology analysis for electrically connected parts, the right and left CP numbers of an open switch are identical only if they are connected by a closed loop. For a closed switch they are always the same.

There are different kinds of topology analysis algorithms possible for different purposes. All can take the same static topology description as a base:

- For interlocking we need to know the electrical potential of a connected part, based just on electrical connectivity. Here the boundary of connected parts is formed by open switches (Figure 2). A connected earth (see CN2 in Figure 2) provides earth potential, a connected generator or incoming line provides active potential. The potential can also be used to color switch yard parts
- For protection functions we are mostly interested in protection zones. These are connected parts, whose boundaries are formed by open switches or by circuit breakers, even if they are closed but still switchable (Figure 1)
- For synchrocheck and synchronization the identity of a VT providing the bus bar voltage might be interesting. Here again the boundary of connected parts is formed by open switches

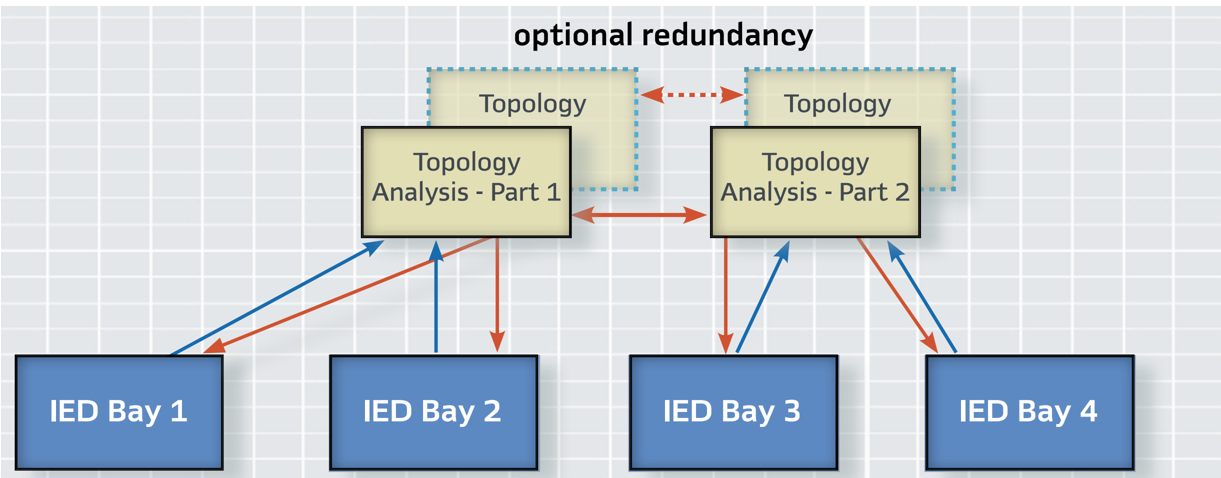
Our line example in Figure 1 shows that we might have connected parts across several substations, in this case the line protection zone. To keep the CN identification codes within substations independent from each other, and allow topology parts across substations, it is recommended that in addition to the unique identification numbers within the substation already mentioned, a second identification number related to a substation (or maybe a voltage level) is introduced. If this part exists, it is first evaluated in the maximum formula for the CP identification, and only if they are equal, the substation internal part is additionally evaluated. This second identification part needs to be globally managed across all independently engineered parts of

Topology analysis is based on connectivity nodes (CN) assigned to connectivity parts (CP).

The introduction of topology aware applications and topology part based message addressing reduces the amount of engineering work, increases the system reliability and reduces negative effects of system extensions on the engineering of system level applications.

By using IEC 61850 based communication between substations, this concept can be extended across the whole power grid, thus getting system level protection by just engineering-wise connecting power grid topology neighbours.

3 Data flow of distributed central redundant topology analysis



The separation of the central topology analysis reduces the amount of messages to be handled by an IED. This might require however each IED to be either redundant, or be replaced in case of a failure within the still alive IEDs.

by Dr. Wolfgang Wimmer, ABB, Switzerland

a power grid used within the same topology aware application.

Using topology properties

The usage of the already determined topology properties, especially the CP identification, is for most applications straight forward:

- **Breaker failure:** the breaker failure trip is accompanied by the two zone identifications at the two sides of the failed breaker. Any breaker knowing to be connected to any of the two zones will trip
- **Bus bar protection:** the trip is accompanied by the identification of the zone to be tripped. Any breaker knowing to be connected to any of the two zones will trip
- **Lockout function:** the lockout setting is done by the zone trip command and therefore accompanied by the zone identification of the zones to be tripped, leading in parallel to a lockout of the concerned breakers. In Figure 1 if the transformer protection trips the green zone, both circuit breakers around the transformer are locked. If a common reset command for the blocked zone shall be used later on, then the lockout function has to store this zone identification, because due to later switching actions the actual zone identification might change
- **Reverse blocking:** the start indication transmitted for blocking is accompanied by the connected part (CP) identification to which the starting overcurrent protection belongs. This allows selective blocking of the overcurrent protection functions at the infeeding bays connected to the same CP

For other application specific functions the usage is application dependent and might need additional CP properties. Here is just one example for the interlocking function, which might also be useful for interlocking between substations:

The interlocking function can use the potential of the connected parts. If a switch is connected at one side to a part with earth potential, and at the other side with active potential, then its closing is forbidden. For relatively simple single line configurations like ring and single bus bar configurations the knowledge of the electrical potential might be sufficient to cover all station level interlocking functionality, thus avoiding substation specific station level interlocking logic.

As can be seen from these examples, using topology aware function implementations reduces the project specific logic drastically. Especially the topology analysis itself can be done just once for all topology aware functions based on the same definition of a connected part, one protection zone analysis can be reused by all protection zone related functions. If an IEC 61850 based implementation is used in a distributed system for this purpose typically using the GOOSE service for time critical applications, we still have to configure a project specific static data flow at the senders as well as at the receivers. The configuration as such can be more or less automated based on a system description in SCL, similar to the generation of the static topology description for use on the IEDs.

However, after data flow generation we still have to marshal the incoming signals into the receivers. If we consider e.g. the zone based tripping and blocking messages above, the engineering effort at the receivers could be drastically reduced by introducing an event or message based real time service, which allows treating the (GOOSE) inputs as separate event messages to a common trip / block handling function instead updating a process image. With other words: the current GOOSE service providing real time state information from the sources needs an enhancement for connecting real time commands from several sources to one destination input, thus providing a kind of data flow based OR function. Before this is available, some GOOSE message building conventions for zone based tripping / blocking could also help to automate this input engineering.

The CP based tripping reduces engineering effort.

Another implementation method to make the incoming data flow at receiving functions independent from the single line topology could use the fact that the IED hosting the bus bar related connectivity node has anyhow to be touched for system extensions at least from data flow point of view. It can also concentrate any trip or block messages by performing a logical OR for all connected bays, resulting in just one output message for all applications connected to this connectivity node. In this case only one message from each topologically connected IED to the bus bar CN host and one from the CN host into the system has to be considered, thus reducing dependencies on the expense of additional message delays.

Enhanced protection reliability by topology aware functions

Due to reduced engineering effort, enhanced tool support, and restriction of IED configuration changes for system level functions at system extensions to only those IEDs hosting the bus bar nodes to which a new bay shall be connected, the availability as well as reliability of topology aware implementations will be higher than for conventional implementations.

As the breaker failure function illustrates, high protection reliability

The usage of the already determined topology properties, especially the CP identification, is for most applications straight forward.

in case of a non-operating circuit breaker can be gained by transferring the trips to the neighbouring zones of the failed breaker, thus possibly propagating a trip across a whole bus bar. This 'zone connection' can be done automatically if a zone trip reaches a circuit breaker which is known to be blocked or defected. In case that this is known before the trip, the topology analysis can already connect the zones at analysis time, thus reducing the time for a zone trip in case of circuit breaker failure conditions. This is especially useful for process bus implementations in case the connection to the breaker IED is lost.

Distributed versus central implementation

What stays to be investigated is the influence of failed Substation automation (protection) IEDs. This naturally depends on the SA system architecture. To profit from the advantages of topology aware algorithms, at least the topology aware actions like trips and blockings should be implemented in a distributed way, may be with some concentration at the IEDs hosting the bus bar related CNs to reduce the engineering influence of system extensions. The topology analysis can also run distributed across the same IEDs, or centrally, in this case just providing the calculated CP identifications and topology properties down to the IEDs in advance of any action. For simple topologies it could also be considered to use a static zone allocation, thus avoiding the need for a topology analysis completely, however at the expense of some additional, mostly bay local application functions to handle specific situations like maintenance or a closed but blocked circuit breaker. The following concentrates on discussing a central and a decentralised implementation of the topology analysis function. Observe that the algorithm description and discussion above was already in view of a distributed implementation.

The implementation of topology based applications can be further enhanced within IEC 61850:

A central implementation of the topology analysis is for sure a single point of failure. Therefore a redundant implementation in form of a hot - standby or hot - hot system is recommended. Observe that the topology analysis needs the static topology, the dynamic state of the switches, and finally some means to publish the calculated analysis result, due to their time critical nature with GOOSE messages. As two identically configured IEDs getting the same state will produce the same results with only small time jitter, this could easily run as a hot – hot system, allowing a fast switchover at the receivers from one IED to the other – however also doubling the amount of GOOSE messages sent from the topology analysis IEDs for this purpose.

Although a central implementation leads to just one place to change in case of system extensions, a disadvantage is that at system extension time the whole functionality is down. With a hot – hot or hot standby system this can be overcome by reconfiguring first one IED and then taking the second one out of service, until the configuration of the first one proves to be OK. After this the second IED is reconfigured and also taken into service. For big systems it might also be considered to separate the central topology analysis into several parts, which exchange state information at some common connectivity nodes (Figure 3). This reduces the amount of messages to be handled by an IED managing only a part, however each part IED must then possibly be redundant, or be replaced in case of a failure within the still alive IEDs by an automatic zone concatenation of all its managed parts, thus reducing the selectivity of the protection but still providing a minimum backup protection in case of a primary fault.

A distributed implementation of the topology analysis is heavily dependent on the IEDs hosting the logic to handle connectivity nodes. In a bay oriented architecture these are the IEDs hosting the bus bar related nodes. If one of them fails, the topology analysis for this bus bar part is no longer available, leading to a block of all breaker failure LNs needing this information. If the system has several bus bar parts whose connectivity nodes are handled by different IEDs, only one of them will be concerned, leaving the rest still operational. If this is not sufficient, this could be overcome by having a 'backup' reference for the failed connectivity node to another connectivity node on another IED, which practically is a kind of preconfigured zone connection.

Extending the concept

The introduction of the IEC 61850 GOOSE service allows implementing time critical horizontally distributed applications like breaker failure protection, lockout, reverse blocking or interlocking by means of serial telegrams instead of cable wiring. However, by just putting the signal engineering on top of serial messages the complexity of application engineering stays. The introduction of topology aware applications and topology part based message addressing reduces the amount of engineering work, increases the system reliability and reduces negative effects of system extensions on the engineering of system level applications.

By using IEC 61850 based communication between substations, this concept can be extended across the whole power grid, thus getting system level protection by just engineering-wise connecting power grid topology neighbours. ■

- **by** Introducing a new receiving concept of GOOSE messages similar to MMS level commands based on application level addressing with a topology part identification
- **by** Modelling the single line topology and identified parts in terms of logical nodes, to allow the reuse of topology analysis data by different distributed and topology aware application functions.

Contact us

ABB Switzerland Ltd
Power Systems
Bruggerstrasse 72
CH-5400 Baden, Switzerland
Phone: +41 58 585 77 44
Fax: +41 58 585 55 77
E-Mail: substation.automation@ch.abb.com

www.abb.com/substationautomation

1KHA- 001 146 - SEN - 05.10

Power and productivity
for a better world™