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# Use of distributed topology detection for applications in Substation Automation

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***Abstract* – Distributed functions in substation automation systems typically use distributed data (sensors) and act on more than one switch, i.e. on distributed actuators. The allocation of a distributed function to sensors and actuators is in many cases not fixed but dynamically depending on the actual switchgear topology i.e. of the actual switch states in the single line diagram. The detection of the actual topology is the key, which may be done in one central IED or in many distributed ones. A special problem is the extension of the substation e.g. with one new bay without reengineering the existing SA part and retesting of the existing part of the distributed functions. It is shown that this goal may be reached with a separate topology detection function which serves all distributed functions. The approach uses a topology detection distributed on several IEDs, since there are at least one or more IEDs of the existing system and typically one or two IEDs added by the extension. Application function examples like interlocking, zone protection like busbar protection, breaker failure protection, distributed synchrocheck, CT/VT plausibility control and topology based protections are described.**

***Index Terms* – Substations, substation topology, single line, substation automation, topology based functions, distributed implementation of functions, communication, IEC 61850, extensions, retesting**

## I. INTRODUCTION

In substation automation (SA) a lot of functions use local data like a measured value and perform a local action like operating a local breaker if the related measured value has surpassed a predefined limit. Local means typically one bay or feeder. Examples are simple protection functions like an overcurrent protection. Also a simple command without conditions shows this local behavior.

Other functions need the information from larger parts of the substation or globally from the complete substation in contrast to the local functions mentioned above. An example is zone protection like a differential busbar protection where many currents are measured and in cause of a detected fault more than one breaker is tripped. Closing a breaker depends normally on the release from the synchrocheck and the interlocking, both functions depending on data (voltages, position indications) from other bays. More demanding, the data sources included depend on the actual positions of many or all switching devices in the substation. The detection of the actual topology is the key.

If all functions are performed in *one single IED* all algorithms run in the same processor having access to all data (sensors) and all changeable/switchable devices (actuators). Any change has an impact on this singular processor, i.e. it has to be touched for an update or reengineering. Users may request retesting. The interruption of system operation has to be accepted.

For many reasons like increased availability, minimized data exchange and a clear allocation of IEDs respectively their functions to the sensors and actuators, i.e. to the bay structured switchgear (single line diagram), also *several IEDs per bay* exist (bay control, bay protection, etc.).

In this case, distributed functions depend on more than one IED, and, therefore, interdependence between the *distributed IEDs exists*. Any change in one IED may have an impact on all other IEDs, i.e. in case of any modification or extension many or all IEDs have to be touched for an update or reengineering. Users will request retesting if they are not convinced that there is no adverse effect by this process, but don’t like it because of the impact of the testing on SA system operation and on the power supply facility of the substation.

The goal of this paper is to show that with a dedicated topology detection function all distributed functions may be designed in such a way that the interdependence of the IEDs is reduced as far as the extension of the SA system by new IEDs does not harm the existing system. This means that the new IED will work only with the boundary attributes of the existing system and that the IEDs of the existing system are able to operate with the data and attributes of the new IED without any reconfiguration. By this, no retesting of the complete SA system is requested.

## II. TOPOLOGY AND CONNECTIVITY

The *static topology* of the substation is given by the interconnected single line diagram consisting of busbars, lines, transformers and switches (circuit breakers, isolators, grounding switches). The actual topology is dynamically defined by taking into account the position (on, off) of all switches.

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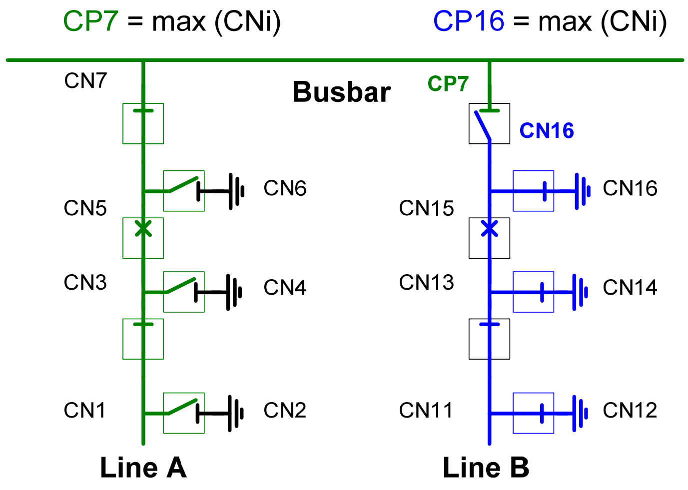

**Figure 1 – Dynamic SA topology as seen in the single line diagram with connectivity node numbers CN1 to CP17 and the resulting connectivity part numbers CP7 and CP16**

To describe this in a formal way allowing easy calculation of connected parts, the topology is described and held on the IEDs as follows:

- 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 equipment references the connectivity nodes to which it is connected.

This defines the *static topology* of the single line diagram, which can then be reused by different topology analysis algorithms to identify different kinds of connected parts. Having the topology references from the equipment to the connectivity nodes (CN), especially the busbar nodes, allows for easy extension of the single line diagram, if it is hold distributed in the system. Any new bay just has to reference at its busbar disconnector(s) the existing busbar nodes to which they are physically connected. The existing part of the system stays unchanged.

To hold the *dynamic topology*, for each kind of topology analysis each connectivity node is assigned to a connectivity part with a CP number and also each reference at an equipment is additionally assigned to such a CP number, telling e.g. for an open switch, to which connectivity part it is connected with its right terminal, and to which connectivity part with its left terminal (Figure 1).
There are different ways to get a common CP identifier. We choose the maximum of all connectivity node numbers and equipment, which are part of the connected part. As any connectivity node only belongs to one CP, the maximum is unique for all CPs. 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.
As a result of the topology analysis the right and left CP numbers of an open or boundary switch are identical only if they are connected by a closed loop. For a closed non-boundary switch they are identical.

There are different kinds of topology analysis possible for different purpose:

- 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 1, Figure 5).
- For protection functions we are often interested in protection *zones*. These are connected parts, whose boundaries are formed by open switches or by circuit breakers, even if they are closed (Figure 2, Figure 3).

After the connectivity analysis each connectivity node and each equipment ‘knows’, to which part it belongs, and which special properties concerning the specific function this part has. If now for some reason an action like a trip within a connected part is needed, it is no longer necessary to determine, who belongs to this part – it is just needed to send out a message demanding the action for this part.

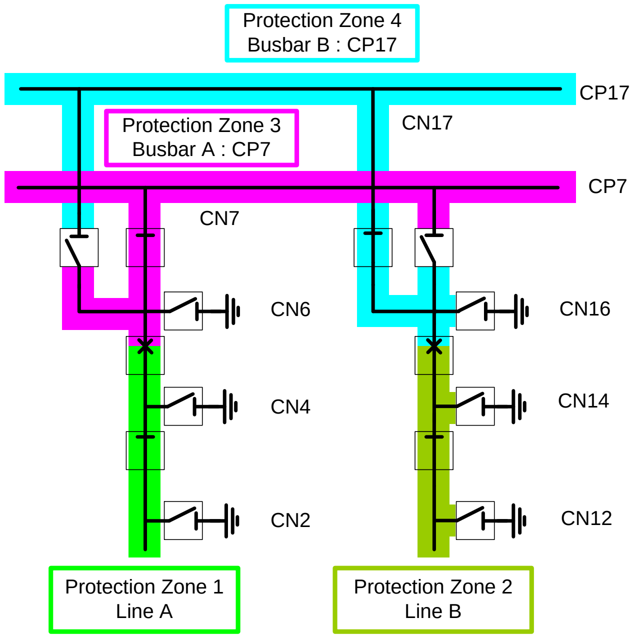

**Figure 2 – Dynamic protection zone Example for Double Busbar Configuration and actual connectivity part numbers CP7 to CP17**

It is important to note that a zone may have at its ends one or more closed circuit breakers which have to be opened all in case of a fault inside this zone. In Figure 2 the zones are split between two busbars and have no connections at all. But the zones may be also arranged in a series as seen in Figure 3. On the left side three zones are electrically connected to one part with connectivity number CP7, on the right side two zones belong to another part with connectivity number CP17. These two electrically connected parts are separated by an open disconnector. The identification of zones and of electrically connected parts as shown in Figure 3, needs two different connectivity analysis processes.

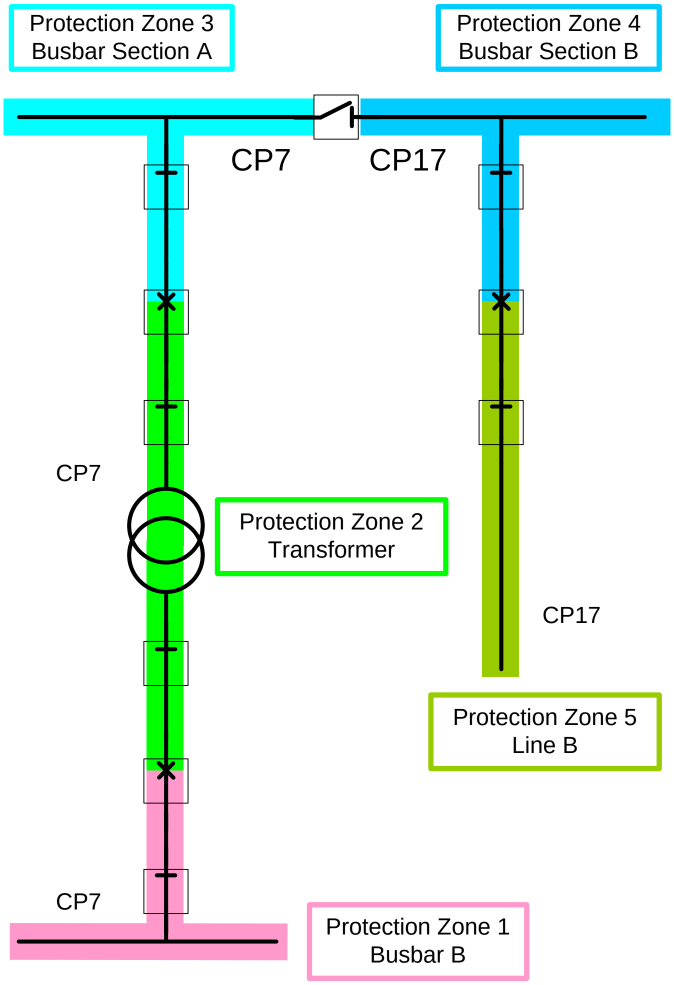

**Figure 3 – Dynamic Protection Zone Example for Single Busbar configuration with a connected transformer and the actual connectivity part numbers CP7 to CP17**

A special case is the *breaker failure protection*. If a breaker fails to open in case of a fault, then all breakers in the protection zones right and left of this breaker have to trip. This is then assured by just sending out a trip command with these two zone identifiers. Any breaker knows if he is connected to one of these two zones and will then trip accordingly. In Figure 4 e.g. the breaker between zones 2 and 3 sends a trip to these two zones. This may be also interpreted as merging of Zone 2 and Zone 3.

*Benefits*: As seen already from the given examples the calculation of connected parts and protection zones replaces a lot of topology dependent logic to trigger specific actions by more simple and general rules based on CP and zone identification. Function specific attribute definitions and the propagation of all these topology based properties between the involved IEDs to be discussed below are fully in favor for this topology approach.

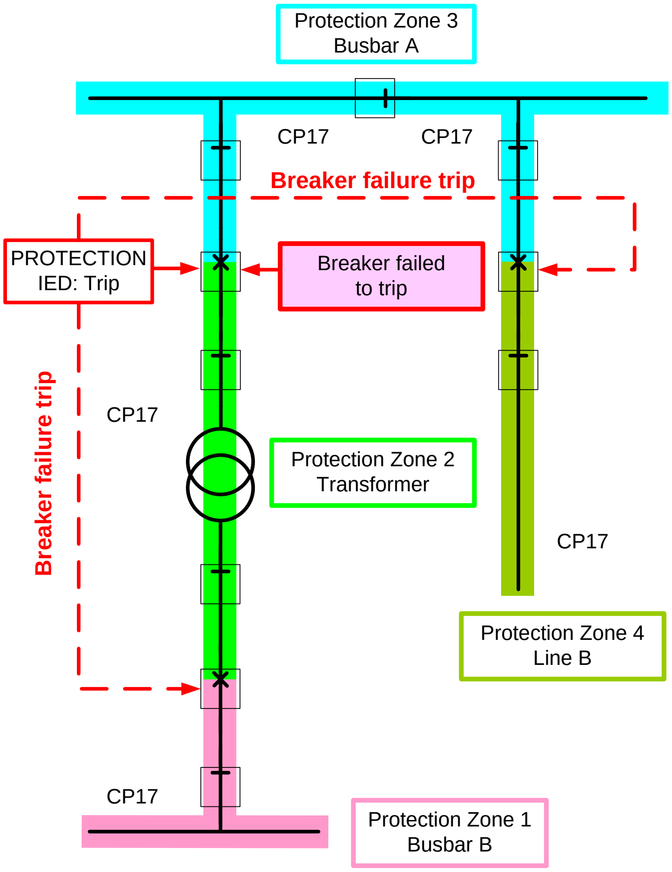

**Figure 4 – Zone-based Breaker Failure Connection for the Single Busbar configuration. The breakers neighboring the failed breaker trip because of messages with right zone identification**

## III. Attribute Definition

Some functions' actions only need the CP (connected part) number or the zone number, others need some additional attributes of the connectivity parts calculated together with the CP numbers. The attributes needed depend on the function under consideration. Some examples are given in the following:

for *Basic Interlocking* [1] the electrical potential of a CP is needed, e.g. with the following values:

- Disconnected (isolated, no potential defined)
- Energized (under voltage)
- Earthed (connected to ground by an earthing switch or a mobile maintenance ground)

- Unknown (if the position of at least one interconnecting switch is unclear)

for *Zone Protection* normally the zone number is sufficient

- Protection zone n (numbered) resp. zone identifier

for *Breaker Failure Protection*

- Back-up zone (numbered) resp. zone identifiers of zones left and right of the failed breaker. For a line breaker this might concern the breaker at the other side of the line

for *distributed Synchrocheck*

- Busbar voltage equivalent zone: the identification of a healthy VT connected to this zone.

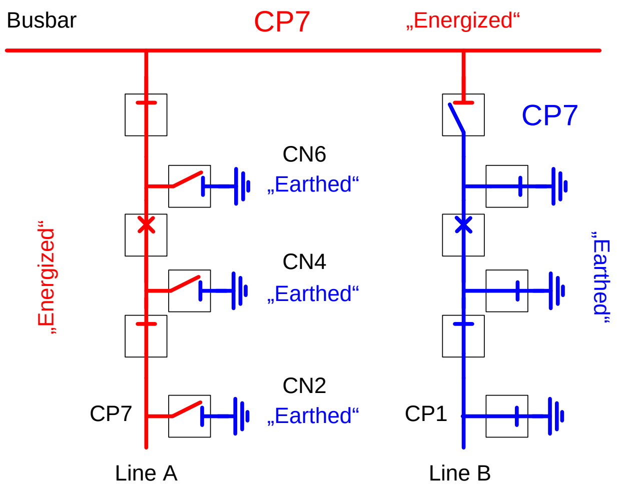

**Figure 5 – Topology Based Interlocking Example with connectivity part numbers and electric potential attributes**

## IV. ATTRIBUTE PROPAGATION

These attributes are calculated and propagated along with the connectivity analysis, i.e. together with the attribute “Connected part n”. The main input is the position of all switches and some boundary conditions e.g. if the line as boundary node is energized, and which switch is an earthing switch. If the connectivity analysis and the attribute distribution are done in one (central) IED, only the needed inputs have to be provided and resulting outputs have to be distributed. For topology based interlocking this is done in one processor or in one processor per bay since long time [1]. For the collection of inputs and the distribution of outputs for time critical functions in IEC 61850 [3] based SA systems the GOOSE messages are very well suited.

If the connectivity analysis and the related attribute propagation are done in one IED (single or multiple), it has to be updated for any change, especially for topology extensions, and during this times the functionality of the distributed function is degraded in all other IEDs also. Here a distributed implementation of the analysis algorithm can help. If the topology detection and the related applications are maximally distributed, i.e. one IED per switch / equipment and one IED per connectivity node, the connectivity analysis and the related applications have to be properly allocated to the IEDs and performed by message passing between them, and the attributes have to be propagated also by communication, e.g. by IEC 61850 GOOSE messages [3]. For distributed connectivity analysis in the best case any IED has only to know the identification of the neighboring connectivity nodes for the equipment objects handled by it. During the analysis the common CP identification as well as its function related attribute(s) are calculated by considering the own state, the last CP state reached, and the state communicated in the messages from the neighbors in the single line diagram. This approach stays valid if the functions and considered equipment are properly grouped, e.g. one IED per bay. In case of a change in one bay or in case of an extension by a new bay only this new IED(s) has (have) to be newly configured and added. All other IEDs of the existing SA system have not to be touched – except that in the case of IEC 61850 devices the neighboring element(s) in the single line have to consider also the new IED(s) as new GOOSE source(s).

## V. APPLICATION EXAMPLES

Typical examples of functions whose implementation can be based on the connectivity analysis are

- Interlocking
- Zone protection e.g. of busbar protection
- Breaker failure protection
- Distributed synchrocheck
- CT/VT plausibility check
- Topology based protection

### A. *Interlocking*

The basic safety related interlocking takes into account the special properties of the switch types, and the electrical potential at its sides. Typical interlocking rules are [1]

- do not connect power to earth
- do not break power with a disconnector
- do not spread earth potential

This means that for interlocking the electrical potential of a connected part is important, additionally to the part identification. This can easily be calculated by assigning each potential a priority e.g. in the order of the enumeration given above, and choosing the maximum potential as CP potential, if an old CP potential meets an equipment or connectivity node related potential [1]. There is one more rule: earth + active = unknown.

Note that for one & half breaker configurations this is sufficient to formulate all non local interlocking rules by local potential and CP identification based rules instead of using switch position based Boolean algebra.

### B. *Zone protection*

If the zone protection function, e. g. a bus bar protection function, has identified an internal fault within a zone, it just sends out a trip command for this zone. All closed breakers knowing to belong to this zone will trip.

### C. Breaker failure protection

If the breaker failure function is activated, it just sends out trip commands for the protection zones at each side of the breaker, and each breaker belonging to one of the zones will trip [4].

### D. Distributed Synchrocheck

The distributed synchrocheck function dynamically calculates the identification of a VT, which represents the voltage of a bus bar node, to which the bay shall be connected.
The connectivity analysis provides the CP identification of the zone, to which the bay shall be connected, at one side of its breaker. By assigning high priority identifications to all VTs, i.e. higher than all other single line elements, and evaluating the maximum element identification of a CP as its identification, directly the appropriate VT identification is known. Alternatively the VT identification can be handled as an own property, distributed in parallel to the CP identification, but with the same calculation algorithm.

### E. CT/VT plausibility checks

VT plausibility checks can be performed by comparing the voltages of all VTs which are electrically connected.
Thus e.g. by calculating an average voltage as CP voltage from the VTs connected together, and then comparing this to the individual VT voltages might give a hint if one of the VTs is no longer performing well. Similarly CT plausibility checks can be performed by summing up the currents of all CTs electrically connected. This needs however another kind of topology analysis as discussed up to now.

### F. Topology based protection

An example of a topology based protection is the reverse blocking, which blocks tripping of the incoming feeders for some time to give the outgoing feeder a chance to clear the (external) fault. The topology analysis finds the common CP identification of connected infeeding and outgoing bays. If the block indication of an outgoing bay is distributed together with this CP identification, then selectively only those infeeding bays are blocked, which are connected to the same CP, i.e. really feed into the outgoing bay.

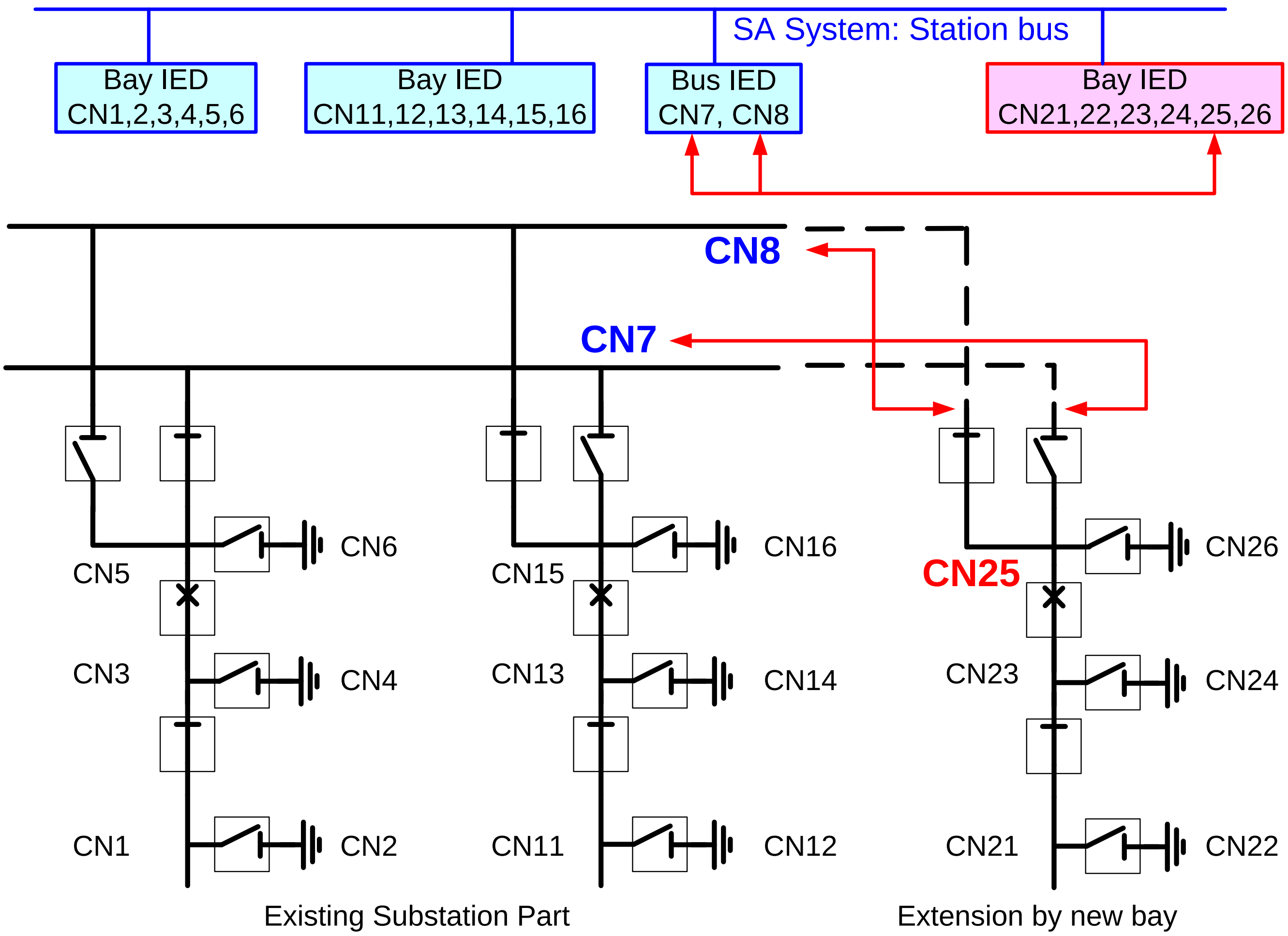

**Figure 6 – Modification example: The extension of an existing substation by a new bay at the connectivity nodes CN8 and CN7**

## VI. IMPACT OF LOCAL CHANGES AND MODIFICATIONS ON THE GLOBAL SYSTEM

As already mentioned above, the influence of system changes, especially extensions, depends on the physical implementation, which can be centralized as well as decentralized.

For the *central version* the central IED has to be reconfigured, and naturally the new IEDs for the new parts have to be configured. At commissioning time, due to reconfiguration of the central part, an interruption of the whole system might happen for a short time. This can be avoided, if (e.g. for availability reasons) the central IED is doubled. In this case the existing (old) system part is still working with one of the redundant central IEDs when the other one is updated with the new part.

For the *decentralized version* those IEDs containing single line parts, to which the new bay shall be connected, have to be reconfigured. This impacts typically one or two IEDs. For a fault tolerant distributed implementation (e.g. merging protection zones if the IED hosting a neighboring part has failed) the rest of the system is always running. In Figure 6 a new IED has to be connected with its bus bar disconnectors to the existing connectivity nodes CN7 and CN8 representing the two busbars of the existing substation. The dedicated bus IED in Figure 6 handles this both nodes, and the new bay IED has to communicate with this bus IED only. Instead of this bus IED this functionality could be implemented in a bus coupler or bus section IED, if any exists. Depending on the implementation concept also the neighboring bay IED could take care of CN7 and CN8 and their connection to the new IED. This is a matter of optimized system design and the IEDs available. The rest of the system now might dynamically get a CP identification 25, if the new bay is connected to one of the bus bars, however this is completely handled by the functionality related to CN7 and CN8.

From system availability point of view a central implementation needs either a fall-back strategy in case that it fails (e.g. bay level protection in case bus bar protection fails), or a redundant central IED. As we have seen, this is also of advantage for system extensions without any interruption of the running system. The distributed approach needs some strategy to overcome lost IEDs carrying a part of the topology. Especially critical here are the IEDs hosting the busbar related connectivity nodes. This fall-back strategy depends on the function. For *zone based protection functions* this might e.g. be merging zones by now choosing a neighboring node hosted in another IED and always assuming to be connected to it, thus still keeping the function alive, but with less selectivity. Unfortunately this strategy does not fit to all functions; e.g. for the *distributed synchrocheck* the connection of two parts which are not electrically connected leads to the wrong voltage source selection.

## VII. CONCLUSIONS

For distributed functions in SA and beyond, the dependency between IEDs and the complexity of action triggering function parts can be drastically reduced, if the actual topology is always evaluated and the appropriate attributes according to the functions under consideration are distributed per identified connected part. This is strongly facilitated by the data model and communication services provided by IEC 61850, especially by the GOOSE service supporting time critical communications between the IEDs of the SA system, although the standard data model will need some extensions to hold the appropriate topology attributes. By a correct allocation and propagation of attributes and a proper design of the functions in the IEDs added for this extension, all other IEDs have not to be touched and work reliable as before. This is true for central applications of the connectivity analysis as well as for completely distributed ones.

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## IX. BIOGRAPHIES

**Klaus-Peter Brand** (SM’89) was born in Neustadt/Aisch, Germany, in 1948. He studied Physics in Würzburg, Kiel, and Bonn (Germany). He got his Master (Dipl.Phys.) and his PhD (Dr.rer.nat.) from the University of Bonn. 1976, he joint the plasma physics group ($SF_6$) of BBC/ABB Research Center in Baden, Switzerland. From 1982, he was in different positions strongly involved developing substation automation systems and building up this business in ABB, Switzerland. He is working at the ABB University Switzerland as instructor and consultant. He is engaged in CIGRE SC B5. From 1995, he is being member of the AHWG and WG10 of IEC TC 57 worked from the beginning defining the standard IEC61850. He is acting now as expert, editor and co-editor of parts of this standard for maintaining and creating the 2nd edition. He is also chair of the Swiss chapter of IEEE PES.

**Wolfgang Wimmer**, was born in Bad Schwartau, Germany, in 1947. He studied Mathematics and Computer Science at the University of Hamburg (Germany), and also got there his Master (Dipl..Inf) and his PhD (Dr.rer.nat.). In 1979 he joined BBC/ABB in Baden, Switzerland. From 1983, he was in different positions strongly involved developing substation automation systems and building up this business in ABB, Switzerland. He is working presently at ABB Utility Automation, Switzerland, as principle systems engineer in the development of substation automation and monitoring systems. From 1996 he is a member of IEC TC57 WG10 working on the standard IEC61850. He is acting now as editor and co-editor of some parts of this standard.