Survey of Smart Grid concepts and demonstrations

Smart substation

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1. Introduction

Distributed generation (DG), electric vehicles, other active resources and extensive cabling of medium voltage (MV) networks will change the behaviour of the distribution network in a manner which also has a lot of effects on distribution substations. The question is how will the role of the distribution substations change if and when the visions of smart grids become reality.

Primary substation is usually intended to be the node point of the system where the voltage level changes from the transmission level to the distribution level. Thus a substation is the connection point between different voltage levels. Reference [Val10] emphasizes data processing functions of the substation. A substation is not only an “energy hub” but also an “information hub”. As the primary substation delivers energy to a large network on a certain voltage level, the substation also monitors and controls the network. The substation is responsible of keeping the network operational and safely running. Many control operations from the network control center (NCC) are focused on the substations.

Smart grid suggestions around the world show how much the control and protection of distribution networks is expected to change within the next few years. As the passive network with unidirectional power flow evolves into an active network with variety of different active resources the requirements for the primary distribution substation will also change, requiring network companies to take action. Network companies do not want to undertake continuous and costly upgrades of the whole protection system but there is still a clear need for adapting to new requirements. The need to increase the level of automation in the distribution system has clearly noticed both on the vendor side [Hec09] and on the utility side [Gor 07].

Various concept levels have been proposed to handle the conflicting requirements for low lifecycle costs and fast new technology utilization. The most traditional approach has been to increase the functionality of the bay level protection and control IEDs (Intelligent Electronic Devices). The issue in this approach has been the extensive costs of upgrades. New features have also required substantial changes in the substation’s secondary system requiring long maintenance breaks.

Another approach proposed by [Vol07] and [Rie05] is fully centralize the functionality in a distribution substation. When all functionality is moved to a centralized station computer the lifecycle of the bay level measurement devices has been greatly extended. Also the upgrade measures needed to implement new features have been simpler, because only the centralized station computer has required updating. When the central station computer is out of operation the protection of the whole substation is lost, however. Fully centralized solutions would always need a redundant protection system – either a redundant station computer or redundant bay level protection and control IEDs – which increase the overall costs of the substation secondary system. The same maintenance problem also exists as with fully decentralized solution. When an upgrade is needed, the whole protection system needs to be upgraded. Long maintenance breaks and extensive testing are required.

Reference [Val09] presents the third approach. It highlights the challenge by combining these two methods. It proposes that only a part of the bay level functionality is moved to a new substation level centralized station computer. The functionality is divided so that the most critical and important functionality would remain in the bay level devices assuring network safety in all situations. This creates the backbone of the network protection system with long life cycle. The functionality defined for the substation level would consists of value added applications and other “nice to have” features for which faster update cycle is necessary. The measures to update the central unit are cheaper and safer allowing smooth utilization of new functions.

2. Requirements for smart substation

In the following central requirements that pose new challenges to substation automation are listed [Val09].

- Regulation rules in consequence of opened free market of electricity distribution (MV)
    - legislation
    - new reporting and monitoring requirements for electricity distribution companies
    - Even short interruptions in the supply need to be reported.
    - Variations in the power quality need to be monitored.
    - The regulation model highlights the quality of the distributed energy
        - higher quality will generate higher profits to network operators
- The control of the network moves further away from the actual physical network.
    - Many company fusions have created bigger players.
- Communication network technology has developed fast over the past years enabling more centralized control
    - increasing need to gather data from larger networks and pre-process data before it is viewed by the NCC personnel
- Rapid increase of distributed energy generation
    - new challenges when the MV network is being used in a different way that it was originally designed for
    - Require fast reactions from electricity distribution companies.
- The maintenance and functional updating measures required by the protection equipment of substations have been time consuming and expensive.
    - switching off the whole protection system and causing interruptions in supply
    - unnecessary secondary testing of the switchgear
- Significant amount of Finnish substation installations start to be outdated and must be refurbished.
- Utilizing of the new protection algorithms
    - need for easily upgraded system without interruptions to customers
- Introduction and the increasing acceptance of the IEC 61850 standard have made available fast and standardised Ethernet based communication.
    - Combining the station and process bus enables an approach where part of the protection and condition monitoring is moved from the bay level IEDs to a centralized Station Computer.

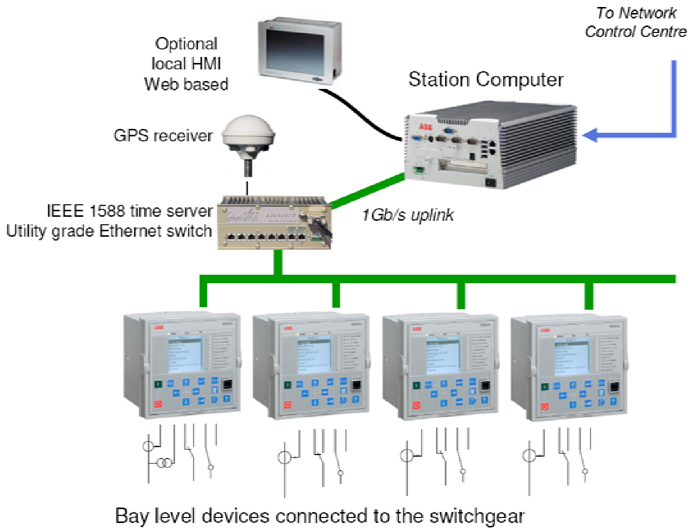

Figure 1. New setup with a central Station Computer [Val09].

Similar approach has also been investigated by Nuon Techno [Vol07], [Rie05]. The main difference to that approach in Reference [Val09] is that in the solution presented not all functionality is removed from the bay level IEDs. The most important and time critical protection functions still run in the IEDs but all additional functionality is moved to the Station Computer. With such setup updating and maintenance activities can be handled without affecting the primary protection.

3. Station level functionality in future smart substations [Val10]

3.1 Division based on functionality

The first division is based on the **importance** of the functions. It includes mandatory functions such as primary protection and control functions.

First functionality group

- These functions must operate within a given short operate time.
- High security requirements – functions need to be backed up and the whole setup is not allowed to fail in operation under any circumstances.

Second functionality group

- Optional functions, such as monitoring and analysis
- Not vital for the safe operation of the network
- Necessary for continuous delivery process.

The second division is based on the **location** of the function.

Unit level functions

- Functions need measured data from the unit e.g. feeder bay.
- The algorithm can be considered “simple” but it can be either a very important protection function (e.g. overcurrent protection) or a value added functionality (e.g. circuit breaker condition monitoring)
- Extensively investigated and widely used in unit level protection and control IEDs

Station level functions

- Need or make use of data from several sources.
- Algorithms can be more complex making the computational requirements more demanding.
- Updated more frequently due to new inventions or new requirements e.g. through legislation.
- Can include both critical protection functions (e.g. high impedance earth fault protection, bus bar protection, etc.) and value added functionality (e.g. fault location algorithm)
- Currently often implemented on the unit level where they sometimes cause unnecessary upgrades of the IEDs and increase the need for communication between IEDs.

The division is presented in Table 1.

Table 1. Functional categories [Val10].

	Mandatory functions	Optional functions
Unit level	Unit level mandatory	Unit level optional
Station level	Station level mandatory	Station level optional

To achieve low life cycle costs for the whole secondary system in substations the life-cycle of each category should be evaluated separately. In general unit level functions should have longer life-cycles than station level functions. There are more unit level devices and they are more closely connected to the electricity distribution process which means longer and more costly maintenance breaks.

3.2 Functionality division criteria

The major functionality division criteria are [Val10]:

- Communication requirements
- Response time
- Utilization frequency (How often these functions are used in real-time operation of the distribution network? Statistics gathered from different disturbances.)
- Function maturity (How often an upgrade of the function can be expected?)

The most self-evident indication for the station level functionality is the communication requirement.

From the communication requirement point of view the following functions are more suited for the station level:

- Protection functionality based on multiple source measurements
  - Advanced directional earth fault protection
  - Advanced directional overcurrent protection
  - Bus bar protection based on blockings
- Control operations based on blockings
  - Interlocking

The desired response time for the function gives a good indication as to if the function should reside on the unit level or on the station level. In general, the faster the function should operate the closer it needs to be the process. Response time limits for the different functions are presented in Table 2 [Abb09a].

Table 2. Response times for different functions.

Functions	
Fast response time	Protection: Overcurrent, earth fault, overvoltage, differential Control: Circuit breaker operation Self supervision: Breaker failure, trip circuit supervision
Slow response time	Protection: Overload, phase discontinuity Control: Disconnector operation, autoreclosure Monitoring: Circuit breaker condition, PQ, disturbance recorder Supervision: IED self-supervision, CT/VT circuit supervision

Function maturity indicates how often an upgrade of the function can be expected. If the function is stable and it is expected to have a long lifecycle functionality wise it is reasonable to locate it on the unit level where updates are more costly. On the other hand if extensive research is going on or requirement changes are expected either through legislation or from the business environment the function should be located on the station level where updating is easier. From this aspect the following areas consist of station functions [Val10]:

- Distributed generation (DG) / distributed energy resources (DER) / electric vehicles (EV)
  - effect of active resources on protection and control
- Fault location
- Post-fault network restoration and dynamic reconfiguration of network topology, self healing network
- Condition monitoring
- Asset management
- Protection against faults with low fault current, e.g. high impedance earth faults

3.3 Unit level mandatory functions

Functionality in this category should be selected so, that the most important features of the unit are secured at all stages. These functions should not rely on external communication so that safety is guaranteed even if communication is lost. The following combination of functions is presented to be mandatory at unit level [Val10].

- Protection:
  - Overcurrent protection (non-directional and directional based on residual voltage)
  - Earth fault protection (non-directional and directional based on residual voltage)
  - Differential protection (transformer, bus bar, etc.)

- Control:
    - Circuit breaker control and operation
- Supervision:
    - Breaker failure protection
    - CT/VT circuit supervision
    - IED self supervision

3.4 Unit level optional functions

As optional monitoring functionality rarely is essential for network safety this category is normally not needed on the unit level, although an extensive library of these functions is available in modern protection and control IEDs.

Following combination of functions is presented for optional functions:

- Protection:
    - Advanced directional overcurrent protection
    - Advanced directional earth fault protection
- Monitoring:
    - Event logs, recorded data banks
    - Simple unit condition monitoring function (circuit breaker, transformer, etc.)

3.5 Station level mandatory functions

Currently this category is not present at all substations. All functionality resides on the unit level (feeder bays, transformers, generators, etc.) and the station level equipment is only used as a gateway for accessing these unit level IEDs. From existing protection functions the following functions can be moved from unit to station level:

- Protection blocking other protection, can block unit level non-directional protection
    - Advanced directional earth fault protection
    - Advanced directional overcurrent protection
    - Bus bar protection based on blockings
- Phase discontinuity protection
- Frequency protection
- Overvoltage protection
- Overload protection
- High impedance earth fault protection (ongoing research)

From existing control functions the following functions can be moved from the unit to the station level.

- Disconnector operation
- Autoreclosure
- Interlocking logic for control operation

Some of the new features needed on the station level concerning to DG are described below.

- Islanding operation and loss-of-mains protection when islanding is not allowed [Rin09]
- Post-fault power restoration [Mek09] and self healing networks in general [Ras09]
- Load shedding [Apo07]

- Automatic recalculation of protection parameters based on topology and DG changes, adaptation of protection

Other mandatory functions on station level are

- Station level supervision
- Fault location functionality
- Cyber-security

While a substation can create a separate secured island for energy distribution it must also provide a bullet proof information firewall for parties communicating with the substation and the distribution network connected to it.

3.6 Station level optional functions

Following functions are presented to be station level optional functions

- Condition monitoring functionality
  - Condition based maintenance (CBM), reliability based maintenance (RBM)
- Outage cost estimation
  - Accurate life-cycle costing
- Recording of interruptions in electricity distribution for statistical analysis

4. Aspects of electricity distribution network company

Reference [Car10] describes the needs of network company concerning to the new primary substation concept. As a main drivers are mentioned

- Renewal asset need
- EU 20/20/20 targets
- Making electricity clean
- Vattenfall smart grid plans
- Cost efficiency in management, operation and purchasing
- Increased customer demands

New substation concept of VF emphasizes

- Standardized software based platform
  - Standard operating system
  - Well defined interface
- Commercial off-the-shelf (COTS) hardware components
  - Standard computers
  - Standard communication products
- Totally integrated software based functions
- IEC 61850 as design base

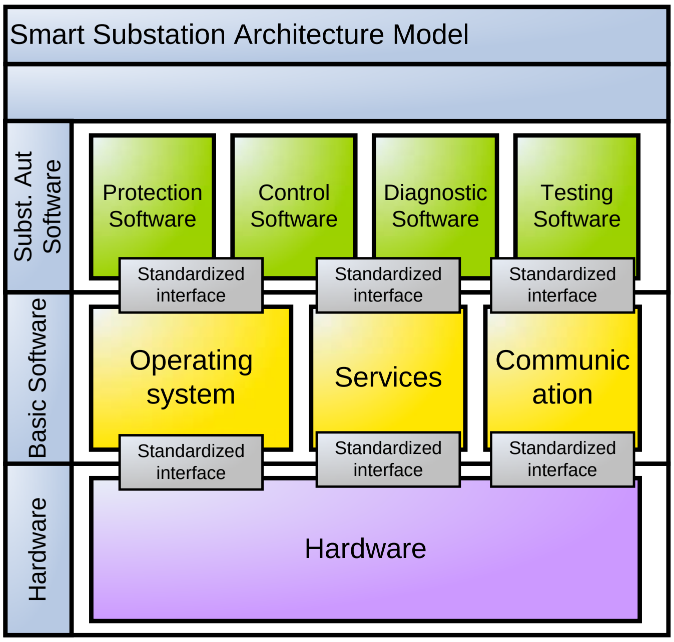

Figure 2. New substation concept [Car10].

Concerning to substation automation software Reference [Car10] highlights

- Basic software platform from one vendor
  - With standardized rules and define interfaces
  - Communication in the substation and out from it
- Software programs from different vendors with different functions
  - The best vendor for each product can be chosen
  - Possible local upgrading
  - Local replacement
  - Easy to introduce new functions

Examples of desired functions are [Car10]

- Integrated software based protection and control
  - Flexible – easily add and remove protection types
  - Adaptive – Automatic protection parameter settings after network situation
- Fault analyse and reporting
  - Auto generated fault information
- Fault location
  - Efficient outage management
- Variable load flow control
  - Required for expansion of DG
- Configuration and testing functions
- Asset maintenance analyse
  - Enabler for condition based maintenance
- Power quality analyse
- Auto generated documentation
- Functions of tomorrow
  - Enable future requirements

The following benefits are pursued:

- Longer lifetime due to software upgrades
- COTS components
- Vendor independent software
    - Better competition due to new players on the market
    - Better products and lower price
- New functions
    - Enabler for Smart Grid
- Remote management

Complex difficulties which are challenging to solve are mentioned

- Responsibilities
    - Software failure on platform or program
    - Hardware failure
- Warranty
- Business model

5. Earth fault protection and compensation of fault current

Reference [Win05] presents a novel scheme for fast earth fault protection. The RCC (Residual Current Compensation) Ground Fault Neutralizer defines new benchmarks for resonant grounded medium and high voltage grids. Safe arc extinguishing is possible also with cable faults. First version of this RCC device was introduced already in 1993 [Win93].

With a total response time of less than 3 cycles the RCC Ground Fault Neutralizer extinguishes the earth fault arc. The significance of this type of applications will increase in consequence of extensive cabling of MV overhead line networks. This type of centralized earth fault protection system including active way to compensate the residual earth fault current is suitable to be presented under the title “Smart substation”.

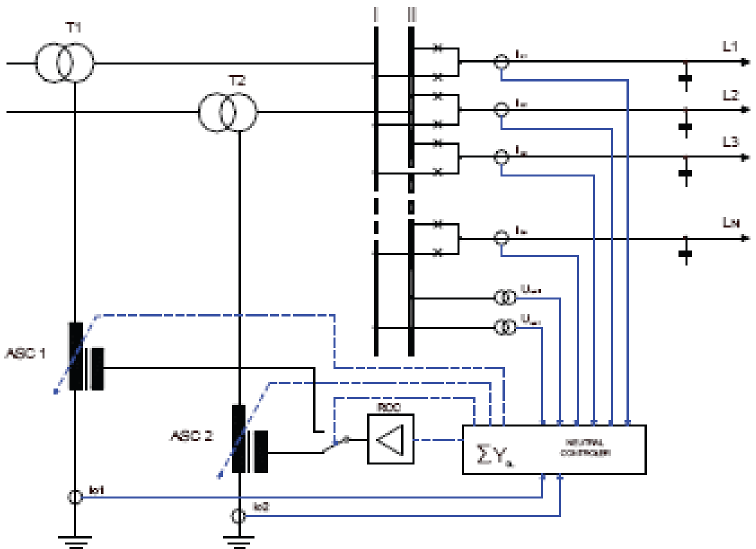

Figure 3. RCC Ground Fault Neutralizer for twin bus bar, block diagram.

6. Centralized feeder protection

Reference [Cer07] describes a new integrated system that provides all functions to protect up to 10 MV feeders and to control a variable Petersen coil connected to the same MV bar using a singe compact device. The "integrated protection system" is a single electronic device installed in correspondence of each MV bar in a HV/MV substation capable to perform the following functions for each MV line feeder supplied by the bar:

- directional earth fault protection
- special protection against re-striking/evolving earth faults
- overcurrent protection
- programmable recloser
- Petersen coil automatic tuning and insulation condition monitoring
- coil efficiency monitoring
- transmission of information to the remote terminal unit (RTU) for the remote control of the system

7. Impact of smart grid on distribution system design

Reference [Bro08] describes and discusses the potential impact that issues related to Smart Grid will have on distribution system design. Functionally, a Smart Grid should be able to provide new abilities such as self-healing, high reliability, energy management and real time pricing. From a design perspective, a Smart Grid will likely incorporate new technologies such as advanced metering, automation, communication, DG and distributed storage. Some of the desired functionalities of utilities and their customers include

- Self-healing
- High reliability and power quality
- Resistance to cyber attacks
- Accommodates a wide variety of DG and storage options
- Optimises asset utilization
- Minimizes operations and maintenance expenses

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