STATION LEVEL FUNCTIONALITY IN FUTURE SMART SUBSTATIONS

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INTRODUCTION

Smart grid initiatives 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 a variety of different active resources, the requirements for the primary distribution substations will also change, requiring the utilities to take action. Utilities 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 been clearly noticed both on the vendor side [Hec09] and on the utility side [Gor07].

Various concept level proposals have been presented in order to address 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). This approach has been sufficient, while CPU capacity has been steadily increasing and the price of new technology has remained at a reasonable level. The issue in this approach has been the extensive costs of upgrades. New features have also required substantial changes in the substation's entire secondary system requiring long maintenance breaks.

Another approach has been to fully centralize the functionality in a distribution substation [Vol07] [Rie05]. By moving all functionality 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. This, however, creates a single point of failure in the substation. When the central station computer is out of operation, the protection of the whole substation is lost. In practice, 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 a fully decentralized solution. When an upgrade is needed, the whole protection system needs to be upgraded. Long maintenance breaks and extensive testing are required.

A third approach addresses the challenge by combining these two methods [Val09]. In this approach 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 back-bone of a network protection system with a long life-cycle. The functionality defined for the substation level would consist of value added applications and other "nice-to-have" features for which a faster update cycle is necessary. The measures to update the central unit are cheaper and safer, allowing smooth utilization of new functions. This paper focuses on a clearer division of functionality – what functions are beneficial to keep in the bay or unit level, and which functions would be more cost-efficiently taken care of by a centralized station computer?

FUNCTIONALITY DIVISION

This paper focuses on two viewpoints for the division of functionality. The first division is based on importance. The first group consists of mandatory functions, such as primary protection and control functions. These functions must operate within a given (short) operate time. Security requirements are high – functions need to be backed up and the whole setup must not fail in operation under any circumstances.

The second group consists of optional functions, such as monitoring and analysis. They are not vital for the safe operation of the network, but they are necessary for a smooth delivery process. If these functions fail, possible fault situations last longer (e.g. incorrect fault location) or fault situations arise more often (insufficient condition monitoring causing faulty estimations of maintenance needs). Inadequate monitoring functionality can also impact profits due to non-optimal utilization of the network resources.

The second division is based on the location of the function. Functions on the unit level only need data from the unit, e.g. a feeder bay. Functionality wise the algorithm can be considered “simple” but it can still be either a very important protection function (e.g. overcurrent protection) or a value-added functionality (e.g. circuit breaker condition monitoring). These functions have already been extensively investigated and widely used in unit level protection and control IEDs.

Station level functions need or make use of data from several sources. Also the algorithms can be more complex making the computational requirements more demanding. The station level functions also are updated more frequently, due to new findings or new requirements, e.g. through legislation. These functions can also include both critical protection functions (e.g. advanced protection algorithms like high impedance earth-fault protection, busbar protection, etc.) and value added functionality (e.g. fault location algorithm). Currently, these functions are often implemented on the unit level, where they sometimes cause unnecessary upgrades of the IEDs and also increase the need for communication between the IEDs. The division is presented in *Table 1* and discussed in more detail in following chapters.

Table 1 Functional categories.

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

The four categories have different requirements – and different execution environments are suitable for different categories. 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 causes longer and more costly maintenance breaks.

Careful attention should be paid to these categories when designing the functional content of the secondary system of a distribution substation. If a function is implemented in the wrong category/environment it can force updates to the automation equipment earlier than otherwise would be needed.

FUNCTIONALITY DIVISION CRITERIA

Finding an optimal setup for distribution automation is a complex problem. Several research papers have been written that assess different scenarios and methods for addressing this optimization problem. Even when we limit the scope to the functionality in distribution substations, the dimensions of the problem are vast. In the following the criteria regarded as most important are presented.

Communication requirements

The most self-evident indication for a station level functionality is the communication requirement. If the functionality requires horizontal and/or vertical communication, in other words needs information from several units, it is beneficial to implement the functionality on the station level. In any case the function cannot perform properly in the case of communication problems, so an implementation on the station level does not lower the reliability.

In general data should be processed at the lowest level possible so that fast and reliable response can be guaranteed. A good practical example of this approach is the human nervous system. When fast response is needed (e.g. when a human touches a hot surface), an immediate command is issued in the spinal cord. Sending the signal from the sensors to the brain and processing it there would create unnecessary delay when the appropriate reaction is undisputable (remove the hand from the hot surface). When more information is needed from other senses (e.g. the surface is not very hot and it is better to look at it first), information needs to be gathered in the brain and processed there.

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
    - Busbar protection based on blockings
- Control operations based on blockings
    - Interlocking

Response time

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 that the function should operate, the closer it needs to be to the process. Another way to express the same result is that functionality can be centralized to the extent that communication delays do not add too much latency and uncertainties to the operation. Functions with short response times are more often unit level mandatory functions, whereas longer response times or no response time requirement at all point toward either optional or station level functionality, or both.

Response time limits for the different functions can be acquired from research papers or from utility requirements. The source of information selected is the technical manual of a protection and control IED vendor [Abb09a]. Technical data provided therein and possible setting ranges for different functions give a good indication on the expected operate speed. With the response time limit is at around 50 ms, a rough division in "fast" and "slow" functions is obtained, see *Table 2*.

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, Auto-reclosure** **Monitoring: Circuit breaker condition, PQ, disturbance recorder** **Supervision: IED self-supervision, CT/VT circuit supervision**

Utilization frequency

Utilization frequency means how often these functions are used in real-time operation of the distribution network. One approach to measuring utilization frequency is to use the statistics gathered from different disturbances in the power system. When a particular fault situation is common in a distribution network, protection against it becomes essential and makes the function mandatory. According to outage statistics for Finnish distribution networks [Ano03] over 80% of the faults in electricity networks happen in the medium voltage network. Of these faults nearly 50% are short-circuit faults and nearly 40% earth faults.

Another approach to the utilization frequency is the technical specification of IEDs. A function, which is almost always present in a protection and control IED, is a mandatory function, whereas functions included only in high end IEDs are more commonly optional. Technical specification from low end protection and control terminals is a good source of information for this criterion [Abb09b]. This information combined with outage statistics gives another approximation to unit level mandatory functions, which in this context can be described as "widespread functions".

- Protection: Overcurrent and earth-fault protection
- Control: Circuit breaker operation
- Monitoring: Measurements, Event logs
- Supervision: IED self-supervision

Function maturity

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. If, on the other hand, 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.

A good overview of this aspect is the amount of research publications in relevant conferences. The level of publications on a topic is in a sense inversely proportional to the maturity of the function. The more research that is going on, the more likely it will be that this year's state-of-the-art concept will be outdated within a few years. From this aspect the following areas consist of station functions:

- Distributed Generation (DG)/Distributed Energy Resources (DER)/Electric Vehicles (EV)
  - Affect 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 magnitude: E.g. high impedance earth-faults

UNIT LEVEL MANDATORY FUNCTIONS

This category is the most traditional category in substations. 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. For smaller stations with lower requirements this category might be the only one needed. This category alone should fulfill the most critical requirements.

Based on criteria presented in earlier chapters the following combination of functions is derived:

- 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, busbar, etc.)
- Control:
  - Circuit breaker control and operation
- Supervision
  - Breaker failure protection
  - CT/VT circuit supervision
  - IED self-supervision

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. For that reason most of the functions are rarely used by utilities, although they can be an important factor in investment and maintenance decisions. The benefit of these functions is also partially lost, when they are implemented on the unit level. As the number of units is large, utility personnel often do not have time to gather and process the data available from these functions. Protection functions operate more on a stand-by manner – when there is a reason to operate, they operate and clear the fault. Monitoring functionality on the other hand requires actions from the operator.

In principle this category would not need to hold any functions. In practice these functions are still needed, because small substations do not require a station level device and therefore some of these functions must reside on the unit level. E.g. in a small substation with just one or a few unit level devices, a station level device would be an excessive cost. But keeping the unit level functionality at a minimum will maintain future upgrade costs at a reasonable level for small substations.

Based on criteria presented in earlier chapters the following combination of functions is derived 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.)

STATION LEVEL MANDATORY FUNCTIONS

Currently, this category is normally not present at all in 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. The drawback of this approach is the update cycle, as already mentioned.

An important feature of the concept outlined in this paper is the transfer from the unit level to the station level of all such functions, which require additional performance from the CPU, data from several other IEDs, or are seen to require more frequent update cycle. The purpose of this category is to complement the functions on the unit level and not to replace them. When the unit level protection can operate without the station level protection, station level functionality can be updated without interruptions. This will also extend the life-cycle of the unit level functions, as most of the update measures are carried out on the station level.

As this category is new to distribution substations, and also consists of new functions subject to a great deal of research interest (and changing requirements), it is not possible to provide as detailed list as for unit level functions. Instead, selections are made from existing functions and results from ongoing research, which fit the properties of station level mandatory functions.

Protection

From existing protection functions based on criteria presented earlier the following functions can be moved from the unit to the station level:

- Protection blocking other protection, can block unit level non-directional protection
    - Advanced directional earth-fault protection
    - Advanced directional overcurrent protection
    - Busbar protection based on blockings
- Phase discontinuity protection
- Frequency protection
- Overvoltage protection
- Overload protection

In protection, there is a great deal of ongoing research especially concerning faults characterized by low magnitude fault currents. This does not require immediate tripping, but the fault can still cause hazardous situations to humans or equipment. These faults also often develop into other fault types with high fault current magnitudes, if not dealt with promptly. A good example of such a fault is the high impedance earth-fault. High impedance earth-fault protection function is a station function. In addition to a frequent need for function updates, many methods have been proposed, which require measurement data from all bays of the substation [Abd09][Abd10], so without station level the functionality could not be implemented.

Control

From existing control functions based on criteria presented earlier the following functions can be moved from the unit to the station level

- Disconnector operation
- Auto-reclosure
- Interlocking logic for control operation

The increasing amount of Distributed Generation (DG) in distribution networks is creating new requirements for the control functionality in substations. The local automation system must react rapidly to changing situations in the network status and topology. Response time requirements can be more stringent than what those achievable from the Network Control Centers (NCC). The substation also needs to be able to handle complex control operations even when the connection to the NCC is lost – islanding operation does not just mean a disconnection from the main electricity network, it may also mean a disconnection from the main communication network. Some of the new features needed on the station level 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

In addition to unit level self-supervision, station level supervision is required. On the station level the requirement is that the performance of each unit meets the set specifications and possible deviations are reported to the NCC.

The fault location functionality has long been more "optional" than "mandatory". But as society becomes more dependent on a continuous supply of electricity, fault location also becomes crucial for the operation of the distribution network. It is also an important part of the power restoration functionality – proper automatic power restoration is not possible without accurate fault location.

The communication infrastructure is becoming more complex, which also makes cyber-security requirements more critical. The substation constitutes a separate sub-network, both from the energy and the communication aspect. As stated in other research reports [Nar09], a secure product is not sufficient, as potential vulnerabilities may arise from insecure integration into existing infrastructures. 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.

STATION LEVEL OPTIONAL FUNCTIONS

It is economical for most of the condition monitoring functionality to move to the station level. Data can be better pre-processed before the utility personnel receive it, and the report is more concise when it is generated on the station level. A station level computer also has more storage capacity for historic information, which is an important aspect for monitoring functions. E.g. the circuit breaker condition monitoring function is often not efficiently utilized, since upgrading an IED has cleared the history. A unit level disturbance recorder often includes storage capacity for just a few recordings and data from intermittent faults is often lost.

Using condition monitoring information for evaluating future maintenance needs is a frequent topic in research publications. Condition Based Maintenance (CBM) and Reliability Based Maintenance (RBM) [Mou97] are a focus for many utilities. Before these methods can be properly utilized, efficient data collection and processing must be possible on the station level [Ang03].

Research also shows how important proper outage cost estimation is for accurate Life-Cycle-Costing (LCC) [Jer09]. Not all equipment requires full-scale condition monitoring functionality, but the need has to be accurately calculated based on outage costs and losses during operation. Also, proper outage statistics need to be collected and processed on the station level.

Changes in legislation cause new and laborious obligations to utilities. Interruptions in electricity distribution need to be recorded for statistical analysis. Customers must be compensated for interruptions exceeding a certain duration. In Finland even the amount of energy not delivered because of auto-reclosing needs to be calculated and reported. More emphasis is now put on power quality and station level functionality for gathering thise data and auto-generation of reports would reduce the workload of the utility personnel.

SUMMARY

The functional division presented here focuses on increasing the lifecycle of the substation automation system by utilizing station level data processing. Initially, the station level functionality criteria are defined. When the function requires communication, but does not have strict requirements for response times, station level implementation can be justified. Complex functionality requiring additional CPU performance and anticipated updates in the near future are clear indications for station level functionality. Based on the defined criteria, existing functionality and current research topics are divided between the unit level and the station level.

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