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Smart Grids and Energy Markets

Survey of smart grids concepts and applications

Editor Pertti Järventausta,

compiled work of several researchers

at Tampere University of Technology

Contents

Preface

This report has been done as a part of the research work of the Smart Grids and Energy Market (SGEM) research programme. The report relates to the workpackage WP1.3 “Migration scenarios towards future Smart Grids” and the aim of the survey of Smart Grids concepts worldwide.

The report is a collection of several literature surveys done by the researchers working in SGEM programme at Tampere University of Technology and one conference paper as such. The report covers more the application level aspects on Smart Grids issues, not so much the vision of Smart Grids in general.

This report constitutes a state of art on the presented topics. Research results achieved in the SGEM research programme under the same topics has been documented in other publications and reports.

Following researchers at Tampere University of Technology have written their own chapter for this report during the autumn 2010: Antti Mutanen, Marko Pikkarainen, Niklas Löf, Petri Trygg, Antti Rautiainen, Anna Kulmala, Ontrei Raipala, Antti Koto, Heidi Krohns, Janne Stranden, Pasi Vuorenpää, Juhani Bastman, Ari Nikander, Pertti Pakonen, Tuomo Vornanen ja Jenni Rekola.

1. Finnish Smart Grids – a migration from version one to the next generation

Authors: Pertti Järventausta, Pekka Verho, Jarmo Partanen, Dick Kronman

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INTRODUCTION

The energy markets are in transition and there are many drivers and needs for creating a new kind of power delivery system for the future, as follows [1]:

- The penetration of distributed generation (DG) will continue due to environmental reasons.
- The European and North American vision is to have common electricity market areas.
- Efficient use of energy at customer level and intelligent demand response have become essential issues.
- Regulation of network companies will tighten up while companies want to ensure the profitability of business.
- There is a need to increase the utilization rate of existing networks. At the same time many components of existing networks are reaching the end of their life cycles.
- Power quality (supply reliability and voltage quality) requirements will increase due to public and regulatory actions and at the same time failure rates are expected to increase due to the climate change.
- The risk of major disturbances is increasing, both the probability and the consequences.

There are many definitions and visions of smart grids worldwide including a vast amount of different characteristics. However, the role of the electricity distribution networks is of great significance for realising these visions. Electricity distribution networks create a market place for small-scale power producers (i.e. distributed generation) and for customers (i.e. users of electricity) in which the quality of service should be at a high level but with reasonable costs. In Finland, about a half of the total price of electricity for small customers and over 90 % of all interruptions are associated with the distribution networks. This emphasizes the importance of the distribution process as well as the societal expectations to develop it further.

Smart grid concept has different aspects as shown in Fig. 1. It includes novel solutions of infrastructure for future power distribution, e.g. use of power electronics and DC. Active resources (i.e. distributed generation, loads, storages and electricity vehicles) actually change the traditional passive distribution network into an active one. New network solutions and active resources call for novel ICT solutions for network operation and asset management providing intelligence to active networks. Smart grids enable active market participation of customers and also have effect on changes in the business environment. Smart grids are customer-driven marketplaces for DG and consumers.

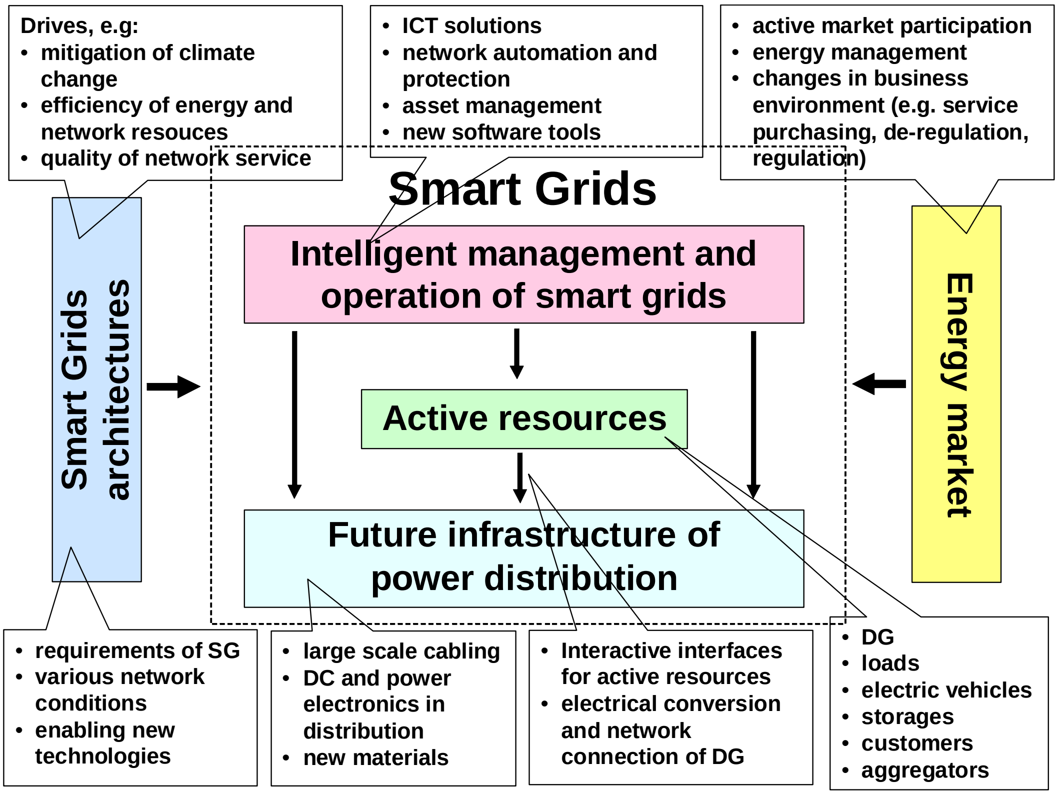

Fig. 1. Aspects of smart grids

Smart grid is not a brand-new concept to be ready 15 years hence, but rather a continuum from previous decades and the systems of today towards the visions of the next generation. The Smart grid vision has to be adjusted to meet the local special characteristics. In Finland, these include e.g. cold weather, long distances between cities, and a large amount of medium voltage overhead lines in the countryside. In Finland, research and development activities have been persistent within the distribution network domain and many novel innovations have been installed by distribution companies in real use during the past decades. There are a lot of applications and solutions which together form the Finnish Smart Grids version 1.0. The paper discusses the main achievements gained so far.

The end of 2009 saw the commencement of a large 5-year national research programme, Smart Grids and Energy Market (SGEM), whose goal is to create the vision as well as the practical solutions for the next generation smart grids.

FINNISH SMART GRIDS – VERSION 1.0

Distribution automation and network management

In Finnish distribution companies the level of automation and ICT systems in network operation is high. First SCADA systems at distribution level were already brought into use in the 70's and the first geographical network information systems (NIS) in the 80's. NIS includes applications for versatile network planning and calculation in addition to network documentation and map drawing. It is a common practice in Finland to have network data available at NIS also from low voltage (LV) network. All customers from the customer information system are connected to network data and the loads of the customers are modelled by hourly load curves in network calculation.

In Finland, the environmental and climate conditions for electricity distribution are challenging due to long distances, broad forests, harsh winter seasons and a large amount of overhead lines which have implied the need for advanced automation solutions for fast fault management and long term network planning. Novel intelligent automation solutions have been introduced already in the 80's in many distribution companies. Such automation applications have been e.g. remote controlled disconnector stations, microprosessor based protection relays at 110/20 kV main substations and real-time distribution management systems (DMS) including e.g. functions of automatic fault location, fault isolation and network restoration of MV-feeders.

In many utilities, the annual outage time of customers was decreased remarkably during a decade as shown in Fig. 2.

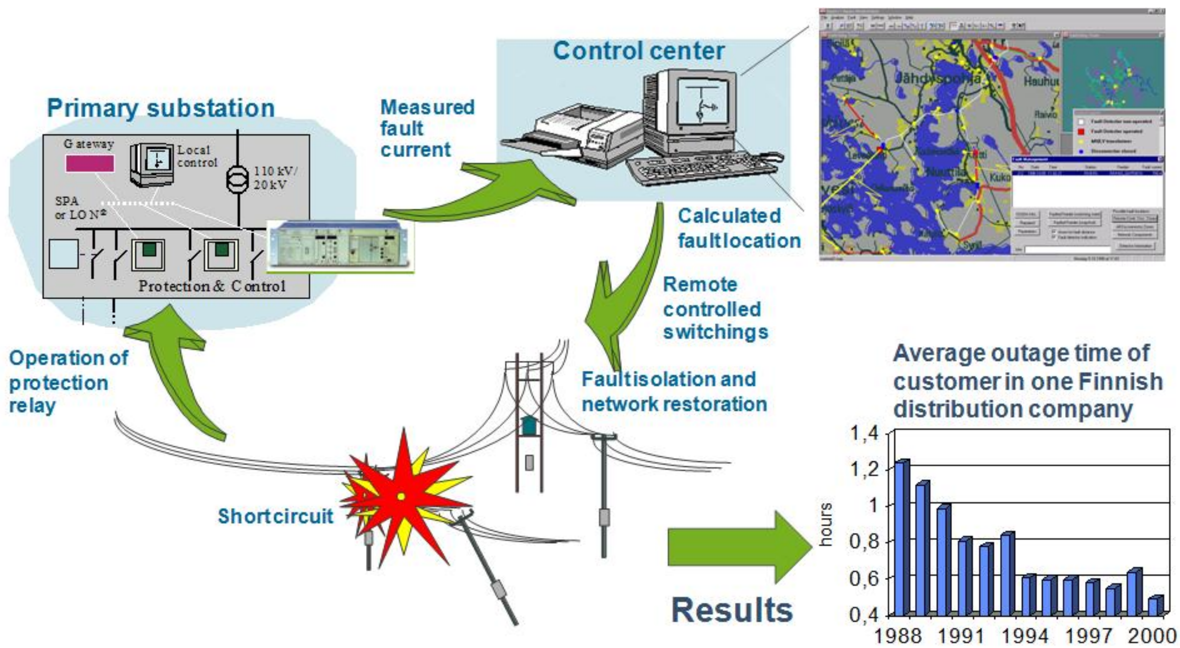

Fig. 2. Solutions for fault management in MW networks

Distribution automation has resulted in good level of quality of supply in rural network conditions with low investments.

During the past ten years many new solutions have been taken into use in distribution companies, such as light 110/20 kV primary substation solutions, pole mounted reclosers, 1000 V distribution system and advanced ICT solutions based e.g. on satellite communication as presented in Fig. 3.

Load and tariff control and remote meter reading through low-band PLC from HV/MV substation to LV customer were used extensively in many utilities already in the 80's.

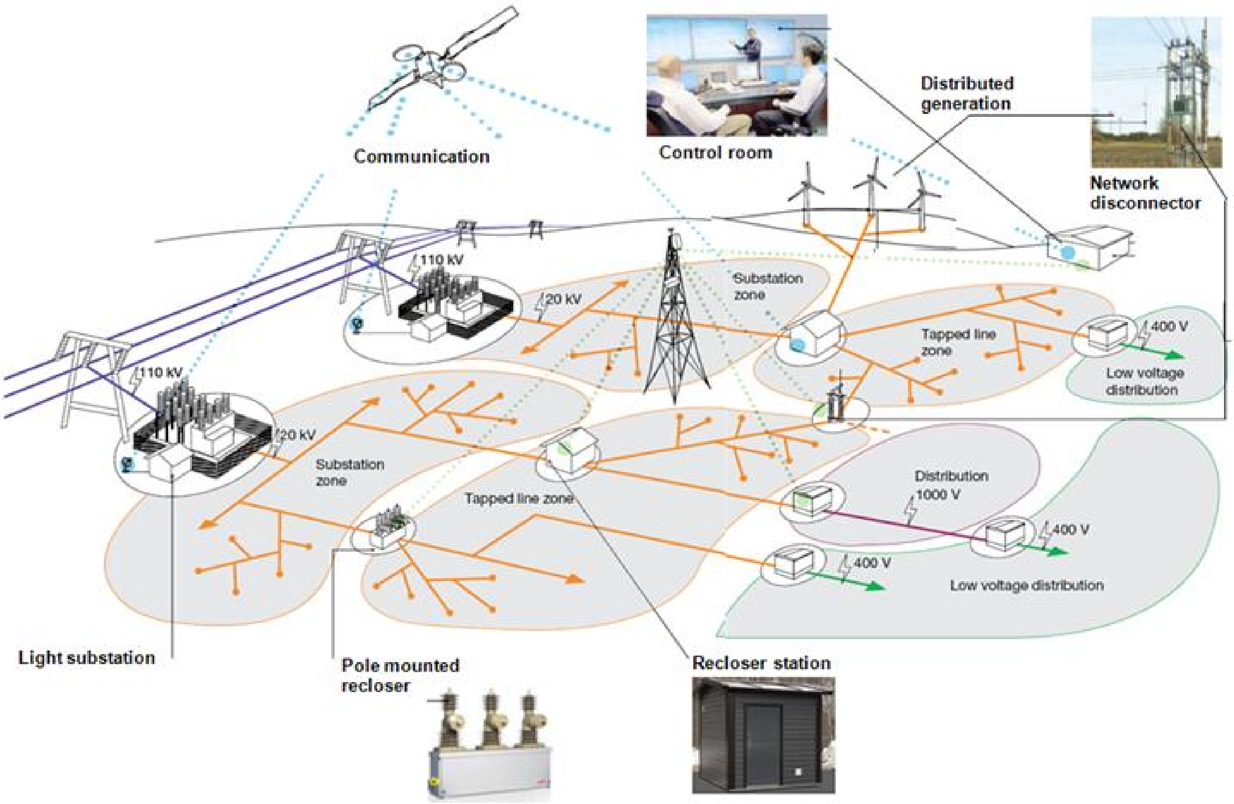

Fig. 3. Comprehensive distribution automation

Utilizing AMR systems in network management

The first generation of AMR systems was already introduced in the 90's. Implementations of advanced AMR systems during the past ten years have already changed the function of the basic energy meter to be a smart terminal unit and gateway that enables real time two-way communication between customers and utilities. In advanced meters e.g alarms based on exceptional events (i.e. network faults and voltage violations) are enabled. The use and integration of an AMR system in network operation can be seen as an extension of SCADA (Supervisory Control And Data Acquisition) and distribution automation to the low-voltage level, as shown in Fig. 4. AMR system can be utilised in many functions of a distribution company, e.g. for supporting network operation (e.g automatic LV-fault indication, isolation and location, precise voltage and load data), network planning and asset management (e.g. exact load profiles for network calculations), power quality monitoring (e.g interruptions, voltage characteristics), customer service, and load control in addition to its traditional use in billing and load settlement [1].

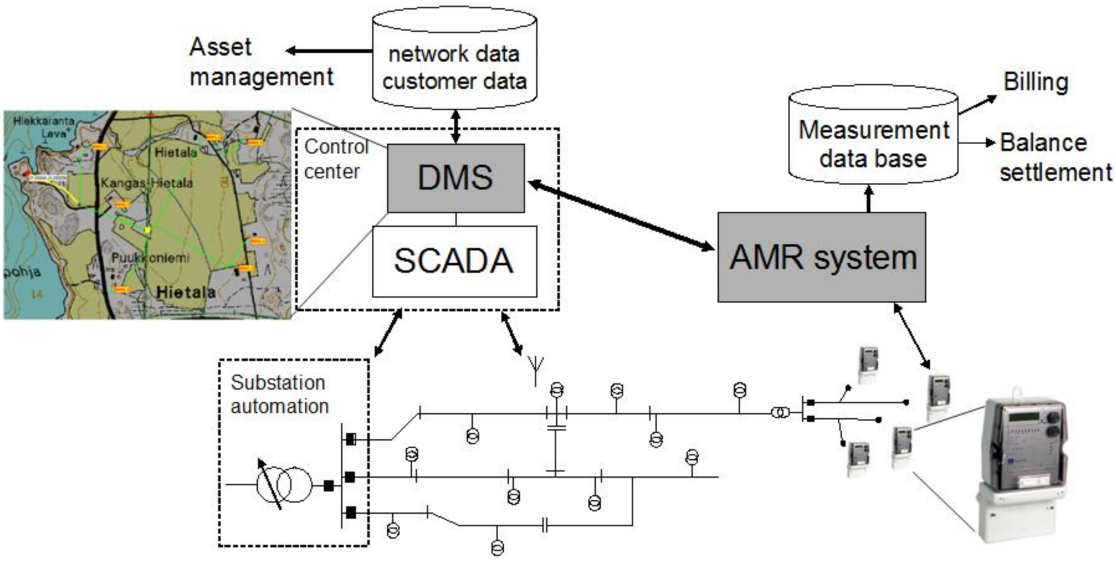

Fig. 4. Distribution network management by using AMR

This kind of comprehensive integrated information system entity based on the installation of an advanced AMR meter to all 350 000 customers is at present in real operation e.g. in Vattenfall Verkko Oy in Finland [2]. Also customer-specific hourly load information can be shown in the web e.g. for energy efficiency purposes.

Legislation requires that from 2013 on all Finnish customers are provided with an AMR meter that features hourly energy measurement as well as demand response functionality.

At present advanced network calculation applications of network information systems and DMS use hourly-load curves as load information. The AMR system offers a large amount of measurement data to determine more detailed load models for different purposes in network management and load prediction [3].

Novel network structures

New innovative network structures have been developed and taken into use in distribution companies during the 2000's, e.g. light 110/20 kV main substation to increase the number of infeed connections, weather proof network [4], 1000 V distribution systems, and low-voltage direct current distribution system (e.g. LVDC with ± 750 V and active voltage control). Fig. 5 illustrates the main principles of LVDC distribution system [5]. The main benefits of LVDC distribution system are a constant quality of customer voltage, lower network investment costs in many cases, better reliability of supply and efficient gateway for distributed small scale generation. The challenges for LVDC are energy efficiency of converters and filters and life time of power electronic components. One significant driver for LVDC is the price erosion of power electronic components. The practical implementation of LVDC distribution shown in figure 5 will be realized during the year 2011 in one Finnish distribution network company.

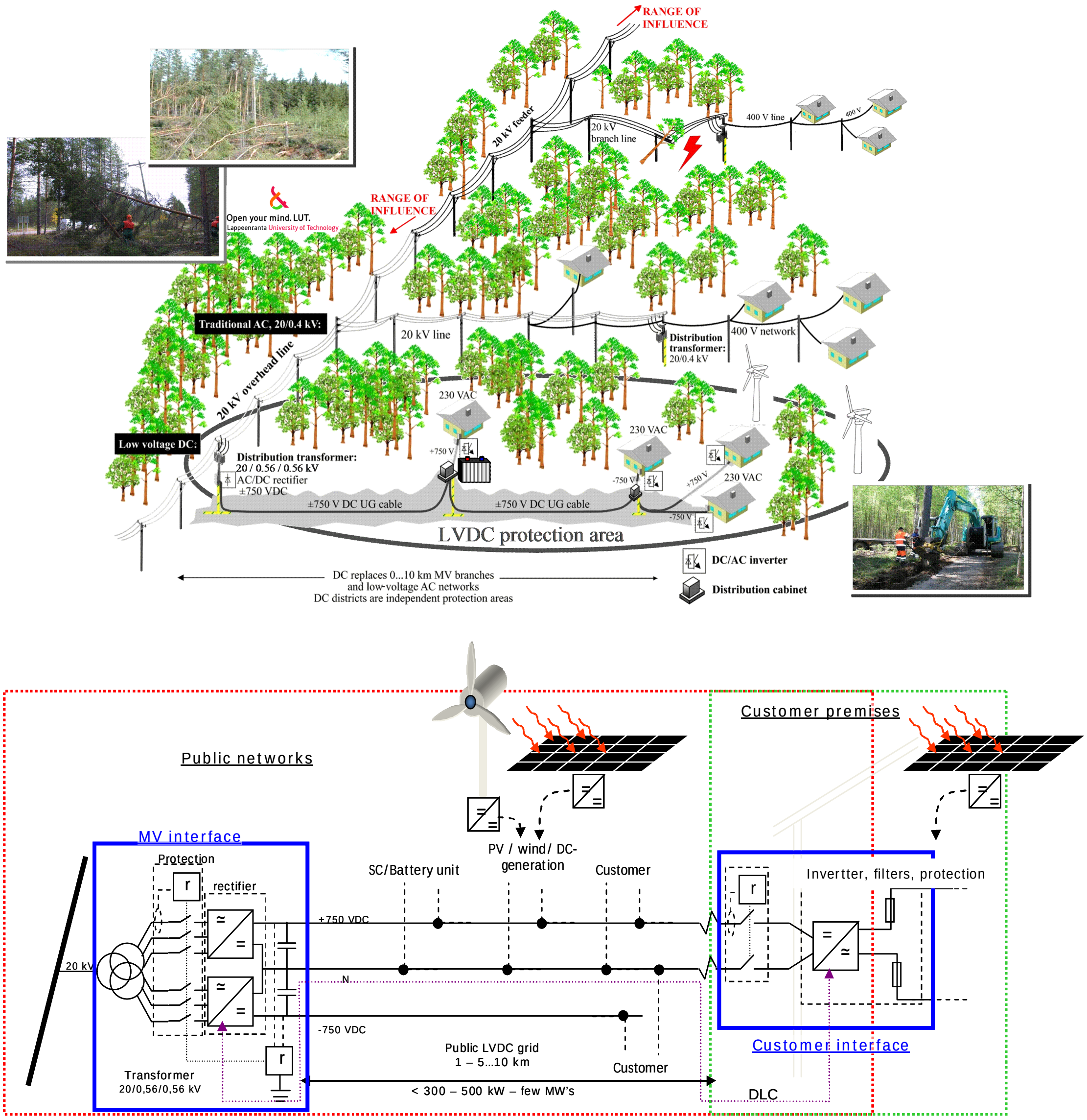

Fig. 5. LVDC distribution system

Nordic electricity market

The electricity market was opened in 1995 in Finland and it is a part of the Nordic electricity market interconnected since the late 90's. Nordic electricity exchange, Nord Pool, is one of the genuinely operating electricity exchanges providing the market price of electricity for various markets (i.e day-ahead, intra-day and regulating power).

Network business and regulation

The open market for service providers was started with network construction in the late 90's and nowadays service purchasing is a widely used and common practice for many functions of network companies. Service providers are private actors with an essential role in the whole network business.

Electricity Market Authority enforces network business. For example, outage costs of both long and short interruptions are part of economic regulation of network companies.

SMART GRID AND ENERGY MARKET (SGEM) RESEARCH PROGRAM

Finnish government has pushed for establishing new non-profit organizations for managing R&D, called Strategic Centers for Science, Technology and Innovations (CSTI). CSTI is a legal company whose shareholders are Finnish major private companies, universities and research institutes. One CSTI, Cleen Oy, was established in 2008 for the energy and environment domain. In the end of 2009 Cleen Oy launched the first research programme, a large 5-year programme called Smart Grids and Energy Market (SGEM) in order to create the vision as well as the practical solutions for the next generation smart grids. The unique consortium consists of almost 20 private companies (e.g. DSOs, power technology and IT suppliers, telco companies and operators) and seven universities and research institutes. The annual volume of the SGEM is about 10 M€/a. The work is divided into several work packages such as drivers and vision, future infrastructure of power systems, active resources (i.e. active customer, customer interface, electrical vehicles, energy storages, distributed generation), management and operation of smart grids, and development of energy market and business potential. Real-life demonstrations are in essential role in the SGEM. Self-healing grids with market based solutions for managing the sustainable evolution of the electrical power system are in the focus of the SGEM.

SMART GRID VISION FOR THE NEXT GENERATION SOLUTIONS

The vision and path forward for the next generation smart grid solutions from customer, society, DSO, TSO and market point of view is defined and is being researched in the SGEM.

Smart Grid has two main functions:

- enabler of energy-efficient and environmentally friendly energy market, which means e.g. interactive customer interface, integration of active resources, demand response, common market models and comprehensive ICT solutions
- critical infrastructure of society, which includes e.g. fault management methods, major disturbance management, self-healing networks, island operation and microgrids

The concept of smart grids may be characterized by words like flexible, intelligent, integration and co-operation. Intelligence means here simply investments in protection, controllability and information and telecommunication technologies instead of pure passive lines, cables, transformers and switchgears. By making the customer connection point more flexible and interactive, the demand response functions are more achievable and the efficient use of the existing network and energy resources by market mechanisms can be improved. Interactive customer gateway opens up possibilities for network companies, energy traders and service providers to offer new kinds of added-value services to end customers. Fig. 6 proposes the concept of the interactive customer interface.

The development towards Smart Grids increases the importance of the LV network automation, which has traditionally been quite insignificant in electricity distribution. The role of the LV automation will be significant in Smart Grids due to advanced metering infrastructure, small scale DG, charging of EV, and concept of microgrids.

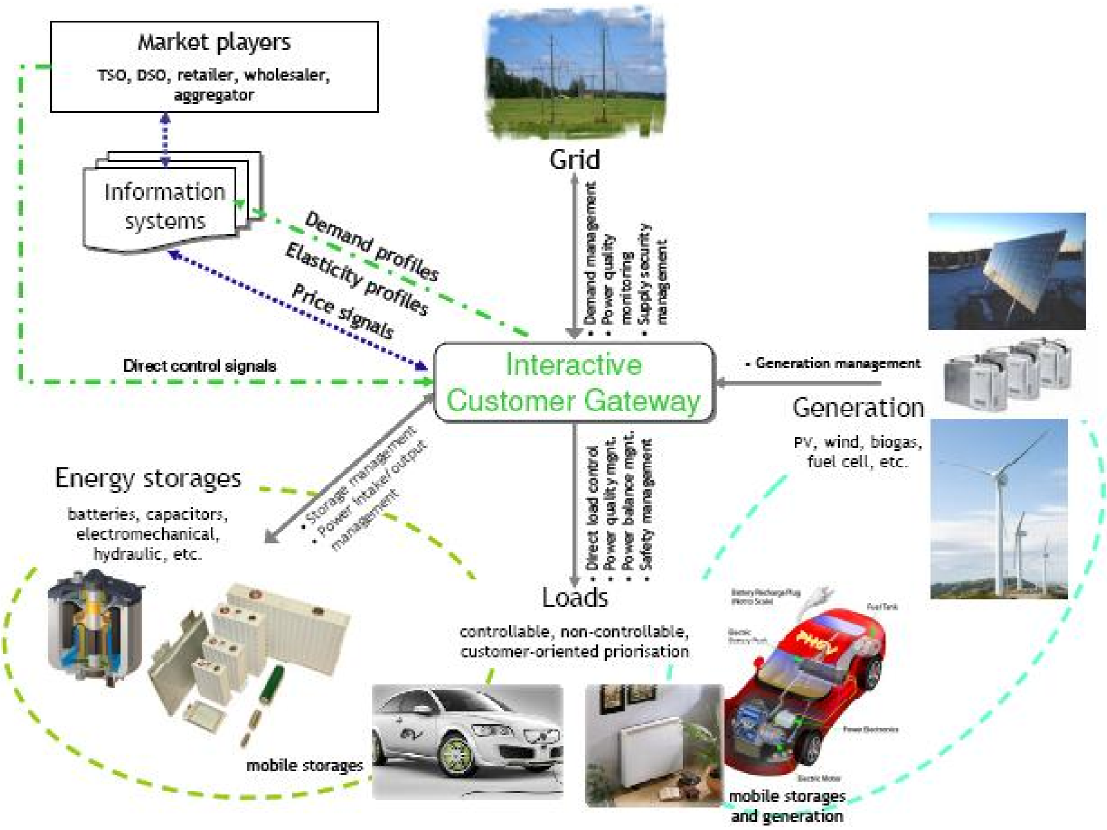

Fig. 6. Concept of the interactive customer interface

Achieving the Smart Grid vision requires development of traditional power engineering but even more importantly large-scale utilization of new communication interfaces and software applications. From ICT point of view, the most significant missing link in distribution networks has been the communication between utilities and end-customers. Implementation of advanced metering infrastructure (AMI) will remove this problem and fulfil one of the most important requirements of the Smart Grid. ICT with common interfaces and data models is an essential enabler of the Smart

Grid. It is needed in all parts of the network to ensure reliable and efficient operation of the Smart Grid.

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2. Use of AMI in distribution system state estimation and load research

Author: Antti Mutanen

INTRODUCTION

The purpose of this study is to examine smart grid concepts and demonstrations from state estimation and load research points of view. Smart grid is a highly elaborate concept of future electricity networks and pretty much every new invention in this field can be included in the smart grid. If I had to explain the smart grid with one sentence, I would say that smart grid is an attempt to maximize the utilization degree of electricity networks and electricity production capacity by leveraging the latest information technology, two-way communication and system intelligence. Of course the smart grid is also much more, but the exact definition is highly subjective.

The need for the smart grid comes from several sources (EPRI 2009). Some examples are given below:

1. Need for power reliability and power quality; the modern society has become increasingly dependent on electricity.
2. Need for energy efficiency; energy costs are rising and it is increasingly difficult to built new production capacity.
3. Need for environmental protection; clean renewable energy sources are often geographically distributed and the existing distribution networks must be prepared to handle fluctuating and bidirectional power flows.

The advanced metering infrastructure (AMI) is an integral part of the smart grids. AMI is needed to realize several smart grid functions. Generally, AMI is defined as a metering infrastructure with two-way communication whereas the automatic meter reading (AMR) has only one-way communication. In this study, AMI is used for state estimation and load research purposes. The existence of AMI or AMR systems makes load research a lot easier than before. Now, historical electricity consumption data is available without conducting separate measurements projects solely for load research purposes. Half of the work – the collection of measurement data – has already been done. The challenge is now in the utilization of this data.

Also the distribution network state estimation benefits from the AMI. When the amount of measurements increases, the knowledge of the network states naturally improves. AMI can be used to improve load profiles through load research or the measurements can be used directly as inputs to the state estimation algorithms. AMI is usually considered to cover only the electricity consumption points, but the smart grid also brings a lot of measurements to distribution transformers and medium voltage network. These measurements are very beneficial for state estimation.

RESENT STATE ESTIMATION DEVELOPMENT

State estimation is a key enabler for any number of “smart grid” applications on the distribution system; these include reactive power management, outage management, loss reduction, demand response, adaptable over-current protection, condition-based maintenance, distributed generation dispatch, integration with transmission system operations, and more. (McDermott 2008)

Currently distribution network state estimators are based on backward/forward sweep load flow calculation. Distribution networks are assumed to be radial and all measurements are assumed to be located on substations. Power flow or current magnitude measurements from the beginning of each feeder are usually utilized in distribution network state estimation. Customer class load profiles are used as pseudo measurements to gain load estimates for the unmeasured parts of the network. The load estimates obtained from the load profiles are not very accurate and there is usually a difference in estimated feeder load and measured feeder load. This difference is corrected by dividing the estimation error to the load nodes proportional to the accuracy of the pseudo measurements. This way the total feeder load is corrected, but the intra-feeder load distribution is still based on the uncertain load profiles.

The state estimation accuracy can be improved by adding measurements to the feeders. The resent development in sensor technology and the emergence of smart grids have brought new possibilities for distribution network metering. Smart grids bring more measurements and telecommunication equipment to distribution networks and thereby enable state estimation improvements. On the other hand, many smart grid functions require accurate state estimates. Thus, smart grid is an important driver in state estimation development.

The need for better distribution network state estimation has been known for a long time. Researchers have been developing new distribution network state estimators for over 15 years. Most of the developed methods are based on the weighted least squares (WLS) approach (Baran & Kelley 1994, Baran & Kelley 1995, Cobelo et al. 2007, Handschin et al. 1995, Lin & Teng 1996, Lin et al. 2001, Teng 2002, Wan & Miu 2003, and Wang & Schulz 2004). There have also been many proposals for improving the existing state estimation methods (Boškov et al. 2005, Hoffman 2006, and Jalonen et al. 2003). Moreover, several other types of methods have been proposed, for example methods based on fuzzy logic (Sarić & Ćirić 2003), calculus of probability (Ghosh et al. 1997) or methods that are combinations of WLS and backward/forward sweep methods (Deng & Zhang 2002). The common objective in all these methods is to use additional measurements better than the existing methods.

WLS methods have been used in transmission network state estimation since the 1970’s. However the application of WLS methods is more difficult in distribution networks because distribution networks have a higher R/X ratio, more current measurements and smaller measurement redundancy. WLS methods are also more complicated and require more computation power than the existing distribution network state estimators. Nonetheless, the development of the new state estimation algorithms has made the application of WLS methods a viable option for distribution network state estimation.

There are two ways to execute the WLS state estimation. The first way uses node voltages as state variables as is done in the transmission network state estimation. The second way, introduced by Baran and Kelley in 1995, uses branch currents as state variables. The latter method has attracted more attention in the academic literature. The branch current method handles current measurements effectively whereas the node voltage method is good in handling voltage measurements. It is widely recognized that the current measurements are more important in distribution network state estimation. There are more current than voltage measurements in medium voltage networks. Also, the accuracy requirements for current measurements are looser than for voltage measurements. A cheap current sensor with 1–3 % accuracy can be very useful in state estimation whereas a voltage sensor with the same accuracy provides only a little improvement to the state estimation accuracy.

So far, the WLS based distribution network state estimation studies have been purely academic. The developed state estimation methods have been tested with computer simulations but no results from real life demonstrations or commercial applications have been publishes. In 2009, North Carolina State University and EnerNex Corporation received a $125,000 grant from California Energy Commission for demonstrating the branch current based state estimation. The goal of this demonstration is to use the branch current based state estimator to help outage management. A Southern California Edison test feeder will be used in the demonstration. In this demonstration, substation measurements are supplemented with AMI voltage measurements from customer sites and current sensors along the main feeder. No results have been published yet. (California Energy Commission 2009 and McDermott 2008)

The above mentioned demonstration project is continuation of a larger research project Load Modeling and State Estimation Methods for Power Distribution Systems (2006–2009). Lately the North Carolina State University has seem to been focusing on using historical AMI data to load modelling and perfecting the branch current based state estimation (Baran et al. 2009 and McDermott 2008). The research is led by Professor Mesult Baran who invented the branch current based state estimation.

LOAD RESEARCH

Load research is the study of electricity consumption patterns for different consumer groups. The pattern of consumption is influenced by many factors and load research is used to estimate the electrical loads for defined consumers or consumer groups in certain conditions. Due to metering costs, the load research is traditionally performed by sampling. The outcome of the load research is a variety of load models. The load models are often statistical in nature.

Finnish load research and current load modelling practices

Finnish load research tradition dates back to the 1980's, when utilities started to co-operate in load research. The load research project was initially coordinated by the Association of Finnish Electric Utilities and 40 utilities joined the project. As a result of this co-operation, customer class load profiles were defined for 46 different customer classes. Since the load models were published, they have been widely used in Finnish distribution network load flow calculation, state estimation, network planning and tariff planning (Seppälä 1996). Later, more research has been done to update some of the load profiles and correct the errors in the load modeling procedure (Jalonen et al. 2003). Some electric utilities have also had their own load research projects where they have for example defined individual load profiles for their largest customers.

Despite some deficiencies, the structure and usage of the load profiles has not changed since the first load models were introduced over 25 years ago. Each individual customer is linked to one predefined customer class load profile by using the information from customer information system (CIS). CISs contain all the available information on each customer's electrical connection, type and electricity consumption. Optionally, some of the largest customers can be modelled with their own models. All the customers are linked to the geographic network model in the network information system (NIS). This enables network calculations using the load profiles.

The load model structure used by most Finnish DSOs' software applications represents the expectation value and standard deviation for the customer's hourly load as a linear function of the annual energy consumption. The load model can be represented either as topography or as index series. In topography, the expectation value and standard deviation for hourly load are given for every hour of the year. Expectation value and standard deviation are usually given for a base energy consumption of 10 MWh/year. In index series, the load parameters are given in a relative form. One index models seasonal variation with 26 two week indices and another index models hourly variation for three different day types (working day, Saturday and Sunday). With these indexes the expectation values for the whole year are modelled with 26*3*24+26=1898 parameters. The hourly standard deviations for the three day types are given as a percentage of the average load. Topographies take special holidays into account, but in the index series public holidays and eves are modelled as Sundays and Saturdays respectively. Both in topographies and in index series the reactive power is calculated using one customer class specific power factor for every hour of the year. In some distribution companies, the reactive power is modelled like the active power with topographies or index series. (SENER 1992)

Finland is a cold country and the outdoor temperature has a big effect on the electricity demand. In distribution network calculation, a simple temperature dependency model is applied. The temperature dependency is expressed as percentage of the load change per degree (°C). The load profiles always give the electricity consumption in average temperature.

Load profiles are also used in balance settlement to estimate the consumption of those end users that are not within interval metering. The load profiles used in the balance settlement are different from the ones used in the network calculation. In the balance settlement, customers are divided into three customer classes and only three load profiles are used. The customer classes are households with electricity consumption smaller than 10 MWh/year, households with electricity consumption larger than 10 MWh/year and others unmeasured customers. (REG 1.3.2009/66)

Legislation requires that at least 80% of customers in each DSO region must have hourly interval metering by the end of the year 2013 (REG 1.3.2009/66). The balance settlement of all hourly metered customers must be based on hourly metered data by 1 January 2012 and immediately for those hourly metered customers that have a retail product based on hourly consumption. All customers consuming over 3x63A are required to have hourly metering by 1 January 2010 (Hull 2009).

Load research in other countries

In many western countries, extensive load research projects were carried out mostly in 80’s. At that time, load research projects were conducted in United States, France, United Kingdom, Germany, Denmark, Norway and Sweden (Seppälä 1996). Later in the 90’s and in the 2000’s decade load research projects were reported from all around the world, for example from South-Africa (Herman & Gaunt 2010, Heunis & Dekenad 2010), Jordan (Elkarmi 2008), Vietnam (McMenamin 2010), Sri Lanka (Jayalath 2009), Korea (Yu et al. 2006), India (Nezhad 2001), Taiwan (Chen et al. 1996), Croatia (Skok et al. 2009) and Romania (Dumbrava 2008). In some countries special organizations have been founded to promote load research for example the Western Load Research Association and the AEIC Load Research Committee in United States and the Load Research Limited in United Kingdom.

The international load research has been mainly focusing on the modelling of the peak consumption or the consumption of the peak day. Many countries with excessive peak loads are conducting load research to find customer groups applicable to their demand management programs. Also, modelling the effect of the demand management is considered an important issue. Load research is also conducted to increase utility’s competitiveness in the liberated energy markets. By knowing customers demand characteristics, utilities can provide their customers with value added services or offer better tariffs.

The main purpose of use for the load profiles seems to be the balance settlement. Ideally, all consumers in an open electricity market should have time-interval meters with online communication. However, since all customers do not have interval meters, the load profiles must be used. If an outside supplier is selling electricity to customers locating in another suppliers network, the electricity sold by the outside customer is first calculated on the basis of the load profiles. The balance settlement between suppliers is then executed according to this estimated consumption. Later, when all the electricity meters are red, the errors between the estimated and measured energies are cleared. Using load profiles allows customers without interval metering to participate in competitive electricity markets.

Several countries use using load profiles in balance settlement as described above (Skok et al. 2009, Dumbrava et al. 2008, Eurelectric 2000, & Maine Public Service 2000). The number of customer classes and thereby the number of load profiles varies from country to country. Some countries get along with three customer class load profiles whereas some use as many as 19 load profiles. The load profiles usually consist of type days calculated for each season of the year or month. Separate type days are usually calculated for weekdays, Saturdays and Holidays. Temperature correction is also widely used. The customer class load profiles are not the only alternative to do the balance settlement. Some countries use area models which are formed by subtracting the interval metered loads and losses related to these loads from the metered area (network) load. The resulting area load profile is then used for all the unmetered customers within the area in question.

As for the balance settlement, the load profiles are often used in a similar way than in Finland. Often the load profiles used in balance settlement are even more detailed that the ones used in Finland. No foreign references were found describing the use of load profiles in distribution network load flow calculation or state estimation – although they are probably used also for this purpose.

Use of AMI in load research

Advanced metering infrastructure (AMI) is one of the key components in the smart grid. AMI records customer electricity consumption hourly – or more frequently – and provides daily – or more frequent – transmission of measurements to a central collection point. AMI is spreading quickly and it is assumed that in the future majority of customers is metered automatically. The amount of consumption data will be enormous. The existence of such a large data set brings new opportunities for load research but also raises many questions. Will this data be good enough for load research? Is there still need for sampling? How this data can be managed or accessed? How will the load research change? Is there even need for load research anymore?

Experiences from the realized AMI projects have confirmed that the data quality is good enough for data analysis and the access to AMI data can significantly shorten the time it takes to implement a load research study. Sampling is still needed for a variety of reasons. It is going to take several years before all customers are within AMI and sampling is needed during this transitional period. When studying very large populations, sampling can be used to reduce computational costs. Sampling also plays an important role in the measurement and verification of demand response programs that are enabled by AMI. (AEIC 2008, Molander 2010)

With the coming of AMI, experience on handling customer usage data is needed more than ever. To correct the errors caused by meter, communication or data handling malfunctions, AMI data is going to need validation, editing and estimation (VEE). This has traditionally been a unique skill set of load researchers. Load research is also needed to extract weather dependency parameters from the AMI data. Since the past consumption has already been saved by the AMI system, the focus in load research will shift to dynamic modelling and forecasting. (AEIC 2008, Molander 2010)

Meter data managements system (MDMS) is a vital component in capturing the desired benefits of advanced metering. Collecting the AMI data is not enough, MDMS must serve as an effective broker between the AMI system and all the enterprise systems that need access to AMI data or AMI actions. In the case of load research, it is important that the load research applications communicate seamlessly with the MDMS. (Aclara 2008)

Different applications require consumption data with different level of validation, editing and estimation, therefore MDMS should be able to store multiple versions of data resulting from different steps of VEE. Depending on the application, MDMS needs to output data that has gone through missing interval check, zero check, negative value check, static value check spike or sum check. For example, Revenue protection applications require raw data and the settlement system requires data processed according to the local market rules. (Aclara 2008) Load research has very high requirements for the level of VEE. The data used in sampling is validated and edited much more diligently than it would be otherwise. While parts of this process are automated and productivity improvements are anticipated, the annual cost to validate and edit interval load data is estimated to be at least 50 US$ per meter. (AEIC 2008)

AMI and MDM systems designed to support smart grids are still under development and their impact to load research is not fully known. It is certain that the availability of interval data provides an unprecedented possibility to create accurate load profiles. Even some have questioned the need for load profiling when we have interval data, load profiles are still needed in several applications. Load profiles are useful in VEE, where they can be used to fill in the missing data (with the appropriate weather modelling). They are needed in distribution network analysis (state estimation and transformer load management). They are also applicable for load forecasting.

Clustering

With the help of AMI it is possible to calculate customer class load profiles. The problem is that the customer classification information is often inaccurate. The current customer classification is based on information available in customer information system (CIS). The type of the customer is usually determined through a questionnaire when the electricity connection is first built. Once the customer type has been determined it is hardly ever updated. In reality, the customer type may change for instance because of a change in the heating solution or an addition of new devices such as air conditioning.

It would be possible to reclassify the customers to the nearest existing load profiles according to their measured load patterns. After this, new updated load profiles could be calculated for the new customer groups. However, if the load profile update is done after the reclassifying, the updated customer class load profile is no longer the nearest load profile for all customers. The reclassification and load profile update should be done again and again until none of the customers change customer class during the reclassification process. Basically, this is a clustering problem.

Clustering has been widely recognized as a viable method for electricity customer classification. Many different types of clustering techniques have been proposed in the literature for customer classification and load profiling. For example, hierarchical clustering, k-means clustering, fuzzy k-means clustering, Weighted fuzzy average k-means clustering, follow-the-leader procedure, principal component analysis, self organizing maps, Sammon's mapping, canonical correlation analysis, probability neural networks, two-step algorithm, fuzzy clustering based on fuzzy relation and several different combinations of above mentioned methods have been applied before for customer classification. (Chicco et al. 2003, Chicco et al. 2005, Chicco et al. 2006, Gerbec et al. 2004, Lo & Zakaria 2004, Mahmoudi-Kohan et al. 2009, Pitt & Kirschen 1999, Ramos & Vale 2008, Tsekoura et al. 2007, Verdú et al. 2004, Yu et al. 2005, Zakaria et al. 2006).

All the studied clustering methods have been found suitable for customer classification. Those publications that have compared different clustering methods have given some recommendations. Chicco et al. (2006) states that the modified follow-the-leader and the hierarchical clustering run with the average distance criterion are the most effective methods for tariff formulation purposes. If computational speed is an issue, follow-the-leader method is recommended because it is 12 times faster than the hierarchical clustering (Chicco et al. 2005). However, the final choice of the most convenient clustering method depends on the application and the operator's needs. In the literature, clustering has been applied mainly for tariff formulation, market strategy planning and balance settlement purposes. In Finland, the need for better customer classification comes from distribution system planning, state estimation and load management.

Most clustering articles do the clustering based on typical daily load profiles. The problem with this approach is that the clustering needs to be done separately for each day type (weekday, Saturday, Sunday) and season. Customer behaviour on one type of a day may be associated to different customer class than the behaviour on another type of a day. Thereby, the customer can have different classification on different days.

Some authors have proposed the use of load profile dimension reduction to simplify and speed up the clustering procedure. The applied dimension reduction techniques are principal component analysis (Li et al. 2008), hourly load profiles, load shape factors and frequency domain indices (Verdú et al. 2004). In these techniques, the dimension reduction has been done for the typical daily load profiles. Verdú et al. (2004) concluded that the best cluster separation was achieved with the hourly load profiles when the original measurements were taken with 15 minute intervals.

When comparing different clustering methods, several different metrics can be used for assessing classification adequacy. The most commonly used metrics are the mean index adequacy (MIA), clustering dispersion indicator (CDI), similarity matrix indicator (SMI), scatter index (SI) and various forms of the Davies-Bouldin index (DBI). A common characteristic of all these indicators is the fact that lower values correspond to better accuracy. Comparison between the clustering results is possible only when the number of customer classes formed by different algorithms is the same. (Chicco et al. 2006)

The electricity consumption data used in the clustering studies has usually been obtained from interval meters. Therefore, the studied consumers are mostly large industrial and commercial customers. Although in some studies, also residential customers have been submitted for clustering. The clustering studies are usually conducted with data sets containing several dozens or few hundreds of customers. The largest data set used in clustering was introduced in (Yu et al. 2005) where 100 000 customers were clustered at once. This huge amount of measurements was collected from the Korea Electric Power Corporation AMR system. In this study, the measurements came from industrial and commercial customers who have over 50 kW electricity demand.

The clustering studies presented in the literature have been purely experimental so far. No commercial applications have been presented.

CONCLUSIONS

The coming of smart grids and generalisation of AMI have clearly increased the interest towards distribution network state estimation and load research. Many smart grid functions require accurate state estimates. Luckily, the smart grid and AMI also enable improvements to the state estimation accuracy. Smart grid brings new measurements and communication channels to the distribution network. In order to utilize these measurements in the best possible way, researchers have been developing new state estimation algorithms for over 15 years. Most of the proposed state estimation algorithms are based on the weighted least squares method. The perfection of these methods has taken a long time and only recently these methods have gotten into the demonstration phase.

AMI reduces significantly the time and resources needed for conducting load research. Measurements collected with AMI can be used for customer classification and load profiling. In Finland, load profiling is done mainly for network calculation purposes whereas in other countries the load profiles are mainly used for balance settlement. Both in Finland and abroad, the modelling of demand response effects is a topical theme for load research.

In the near future, AMI will partly replace the need for load research. For example in Finland, the balance settlement will be done according to hourly metered data by the beginning of 2012. Since the past consumption has already been saved by the AMI system, the focus in load research will shift to dynamic modelling and forecasting.

The customer classification problem is closely connected to load profiling. The use of customer class load profiles requires that the customers are divided into groups with similar consumption patterns. Clustering methods can be used for this task. In the literature, many different clustering methods have been successfully applied to customer classification. The choice of the best clustering method depends on the application which uses the load profiles.

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3. Using AMI in voltage monitoring

Author: Marko Pikkarainen

INTRODUCTION, WHAT IS SMART GRID

The distribution network environment is facing big challenges in the next few decades. The way how to use and generate electricity is changing. Growing concerns about greenhouse effect has affected to political decisions to reduce greenhouse gas emissions especially when the global energy demand is growing. Rising energy price is forcing customers to use electrical energy in an environment friendly way. The biggest hopes of greenhouse gas emission reduction has been given to renewable energy resources often thought as distributed generation and energy efficiency improvement. The technology development has made it possible to decrease manufacturing costs of devices that are capable to those requirements so that normal customers are able to buy those devices. Examples of these devices are: compact fluorescent lamps and heat pumps (to increase energy efficiency), small scale wind turbines and solar panels (to increase renewable distribution generation), and electrical vehicles (to save costs of compared to use of other energy sources/growing electricity demand). [1]

Design principle of distribution networks has been based on centralized energy generation and passive linear loads. Historically the management of distributed electrical energy in distribution networks has based on one way energy flow and active control in higher voltage levels. The force of distributed energy generation is changing this operation model. Because distribution networks have been designed to fulfill different kind needs it is obvious that some problem might occur. If the mass penetration of distributed generation starts before anything is done the interruption rate might increase dramatically.

All over the world many analysts, utilities and governments are hoping that smarter use of distribution networks could provide adequate infrastructure to handle needs of future electricity. For example, in USA president Obama to directed 4.5 milliard dollars towards Smart grid projects and initiatives [1]. But what is Smart grid or smarter use of distribution networks? European Regulators Group for Electricity & Gas (ERGEG) has made one good definition for Smart grid. They state that “Smart Grid is an electricity network that can efficiently integrate the behavior and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety “ [2] .

In addition of above mentioned Smart grid drivers research “The Smart Grid 2010: Market Segments, Applications and Industry Players” made in Greentech Media shows 6 more drivers. Those drivers are: energy independence and security, economic growth, technology advancement, increased efficiency through grid optimization, advanced customer services and 21st century power quality. [1]

This paper is a survey of Smart grid concepts and demonstrations worldwide. It will focus voltage quality monitoring especially using AMI. First it will review the importance on one smart grid driver 21st century power quality deeply. Next it will give a view of voltage quality monitoring using AMI. After that paper will compare the state of the art technology in voltage monitoring in Finland with global view. Finally paper will present some research needs in the field of voltage monitoring.

POWER QUALITY IMPORTANCE IN DISTRIBUTION NETWORKS

In this paper we are considering power quality as the basis of standard EN 50160. The standard defines, describes and specifies the characteristics of the supply voltage in low and medium voltage level concerning frequency, magnitude, waveform and symmetry of the line voltages. These characteristics are subjected to variations during normal operation and vary in manner which is random in time and location. For some quantities of power quality standard EN 50160 says that it is very difficult to give useful definitive values, because some phenomena affecting to voltage are unpredictable. Standard EN 50160 gives characteristics to continuous phenomena, like power frequency, supply voltage variations, rapid voltage changes, supply voltage unbalance, harmonic voltage and mains signaling voltages, and voltage events, like interruptions of the supply voltage, supply voltage dips/swells and transient overvoltages. [3]

The society has come increasingly depended on electricity. The standard of living has increased significantly. Decreasing the number of power outage is increasing its importance not only in industrial view point but also in domestic customer view point. For industry power outage means costs. In the USA economy losses are estimated to be 150 milliard (104-164) dollars each year due to power outages. The cost of power interruptions depends on the field of industry. Table 1 shows how much is the average cost for one hour of power interruption for different industry and how much it is varying between different industry. [1] It is also stated that adequate electricity supply assure a growth economy. [4]

Table 1. Comparable outage costs by industry in USA [1]

AVERAGE COST FOR ONE HOUR OF POWER INTERRUPTION.	
Industry	Amount (U.S.)
Cellular communications	$41,000
Telephone ticket sales	72,000
Airline reservation system	90,000
Semiconductor manufacturer	2,000,000
Credit card operation	2,580,000
Brokerage operation	6,480,000

In addition critical access to electrical power our modern digital life is increasing the demand of other power quality quantities. More appliances that are requiring better voltage quality are coming to the market and are connected to distribution network all the time. With poor voltage quality these devices may malfunction, fail prematurely or not operate at all. In historically and even today distribution utilities have concentrated to power outages rather than voltage quality issues because it more often affect to bigger number of customers. When considering for example the importance of data centers or hospital equipments functioning properly it is obvious that if those are sensitive loads they will require proper voltage quality. It is also possible that in the future customers will pay different prices for different level s of power quality. [1] The most commonly reported symptoms of voltage quality are light flickering, circuit breaker tripping and computer locking up or restarting. Also some damages are reported due to voltage quality problems. [5] In Finland these reasons are also the biggest ones for power quality complaints made by customers as shown in Figure 1. Figure 1 presents the distribution of power quality complaints in one rural area distribution utility in Finland during the years 2003-2005. Flicker is the biggest one, and then are voltage levels and then device breakdowns and lamp burnings.

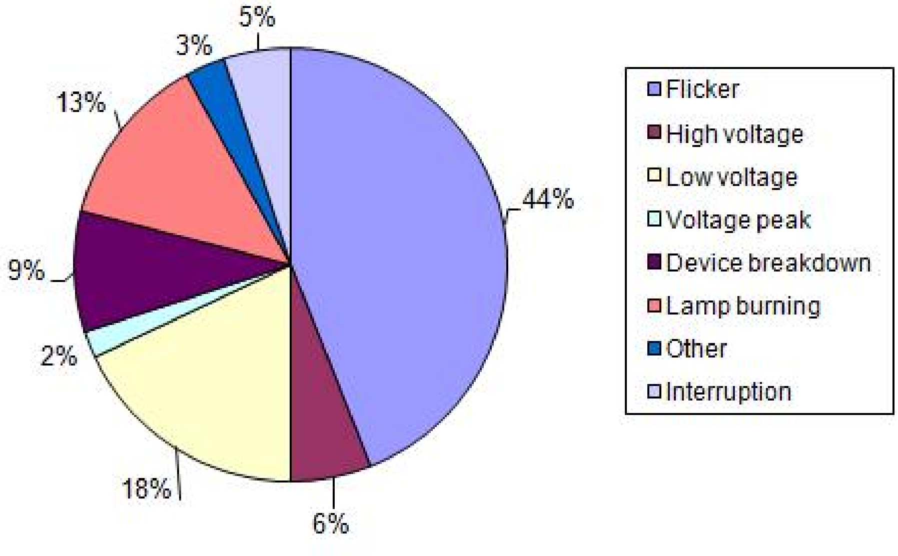

Figure 1. Distribution of power quality complaints in one distribution utility in Finland during years 2003-2005 [11].

Reasons for voltage quality problems may reside in customers own supply network, in other customers supply networks or in the distribution network. Common causes for voltage quality problems are faults, lightning, capacitor switching, harmonic resonance, starting of large loads, overloaded or unbalanced equipment, high-impedance connections, poorly designed power conditioning equipment and poor grounding. [5] [6]

Another view of importance of voltage quality is to consider the financial impacts due to voltage quality problem. It is estimated that voltage quality problems are causing 15 milliard - 24 milliard dollars economical losses in USA annually. It is not very big amount compared to total economical losses produced by outages, about little over 10 %, but it is expected to increase in the future because the number of sensitive loads connected to distribution network is increasing. [5]

One way to exploit increasing possibility of power quality disturbances is to consider heat pumps. Ground source heat pumps have been pointed out to increase flicker level. [7]. The number of heat pumps is increasing. For example in Finland some domestic customers are replacing an oil heating system to a heat pump or to add an air-to-air heat pump in complement electric heating. Also in Finland support from government has speeded up this change [10]. Figure 2 shows the number of installations of different types of heat pumps in Finland during the years 1996-2008. As shown in Figure 1 the number of heat pumps has grown very rapidly during past few years [8]. The growing trend has been the same all over Europe. The overall percentage of heat pumps of all heating types is not very massive in Europe but for example in Sweden heat pumps are the most common heating system in single-family houses with an approximately 34 % share of all. [9]

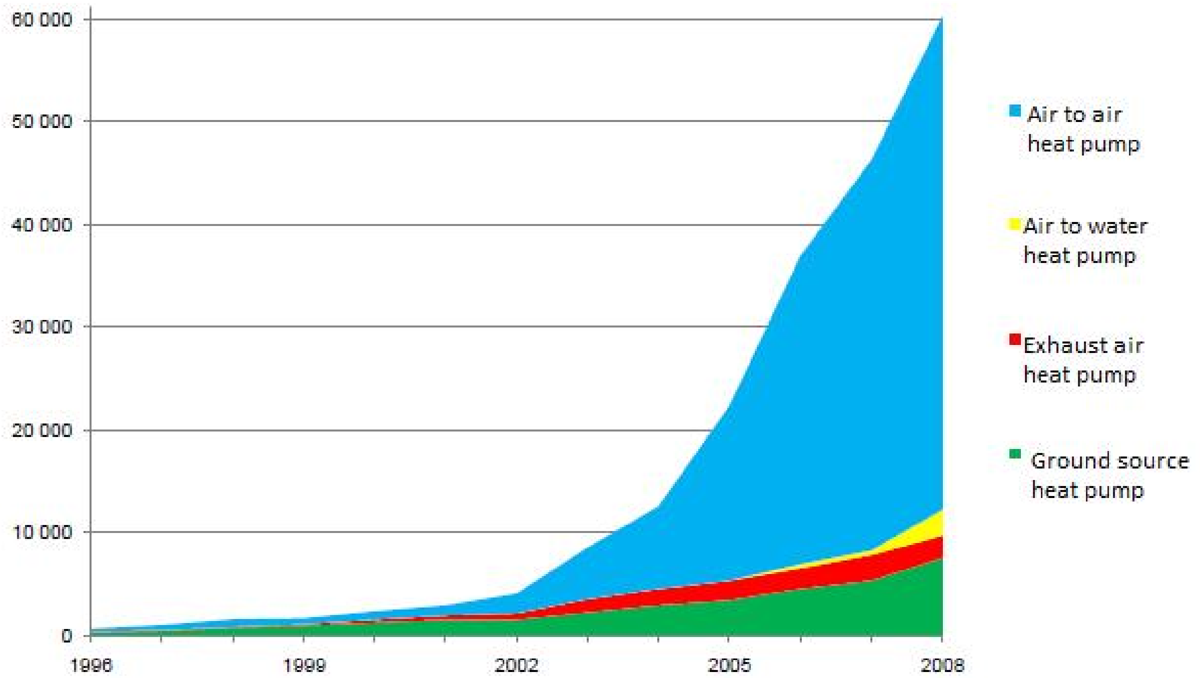

Figure 2. Number of installations of different heat pump types in Finland during years 1996-2008.[8]

Historically power quality measurements are based on centralized measurements in MV level and case specific measurements in LV level. Outages, frequency problems and too low voltage level in MV level have been spotted from centralized measurements. Other power quality disturbances have been clarified with case specific measurements. Reasons for case specific measurements are customer complaints and clarification requests.

Considering these facts it is obvious that constant power quality measurement will be important in the future. These power quality measurements should be extended to every customer point. In addition with measurements there should also be some power quality control ability that requirements of smart grid could be fulfilled.

VOLTAGE QUALITY MONITORIGN USING AMI

AMI is said to be the foundation of the Smart Grid. It "refers to a system that collects, measures and analyzes energy usage by enabling data to be sent back and forth over a two-way communications network connecting advanced meters ("smart meters") and the utility's control systems". The AMI system consists of two main components physical smart meters and communication network. Smart energy meters are playing big role at first stage in Smart Grid technology adaption. Smart energy meters are very easy understandable technology, because there have always been energy meters in the grid, even though those not represent comprehensive vision of Smart Grid. Those meters will provide more information from the grid than it is available before. The other component of AMI is as important as the first one. Without prober communication network the information that is produced will be wasted. [1]

Another way to describe AMI is to explain it as having two distinct layers: the application layer and the transport layer. "The application layer is concerned with data collection, monitoring and operational control, related to effectively managing the over-all electric grid." Data analysis is also in the application layer. The purpose of data analysis is to convert enormous amount of data to actionable intelligent. Those actions are meant to help achieve efficient and adaptive delivery and utilization of power and ensure reliability and security. [1]

The main focus of transport layer is in information flow what is moving back and forth form utility to the energy user. To achieve information flow there are several interconnected networks where the data is moving. The reason why this layer is important is that build out transport layer will allow advanced applications to operate. Some new applications that AMI could provide are: remote meter reading for billing, outage detection and management, and distributed generation monitoring and management. [1]

AMI system is said to collect, measure and analyze energy usage. To perform this AMI system need to have information about voltage and current in every customer connection equipped with smart meters. If the voltage information is not just sophisticated guess it will give some information about the voltage in different connection points. Depending on the way of performance of voltage measurements it will provide information about voltage quality, at least about some power quality quantities. AMI is also able to produce voltage quality monitoring application.

In addition of voltage measurement a proper current measurement could provide critical information to voltage quality monitoring application. With current measurement it could be possible to clarify a cause for power quality disturbances. This could short the clarification time of power quality disturbances and make it more efficient. If the clarification time decreases also it could speed up decisions and acts of how to decrease the effect of disturbance. Most of the labour costs of power quality disturbance clarification could be avoided because the need for case specific measurements could decrease. Also customer satisfaction level could increase because power quality disturbances could be detected before customer complaints about power quality problems.

The biggest advantage of using AMI in voltage quality monitoring is that when every customer point are equipped with smart meters, that are able to provide voltage quality data, awareness of voltage condition in distribution grid will cover entire distribution network. This is enormous improvement to old practice where only information about voltage was voltage level from MV side.

Other view about the importance of voltage and current monitoring using AMI is that it will provide data not only to voltage quality or power quality monitoring application but also to other Smart Grid applications. Those measurements are essential part of active and reactive power and energy consumption measurements. Voltage level information can be used in coordinated voltage regulation applications for example to control power flows from distributed generation sources. Coordinated voltage regulation, allowed islanding operations and active control of energy storages could then provide control abilities to power quality management applications.

One interesting application that voltage and current monitoring could enable is load signature application. With this application it might be possible to estimate (even clarify) what kind of loads are connected into grid, what are the operation schedules of these loads, even what are the CO2 foot prints of different loads and what is the opportunity for demand side management in specific time. These estimations can cover the present time or it can estimate future time. [12, 13]

Voltage and current monitoring using AMI is very crucial in voltage quality monitoring and management applications. Those measurements will also produce lots of data that can be utilized in many different applications. It could also be described that voltage and current monitoring using AMI is the eyes and ears of Smart Grid at least in the low voltage level. Without proper measurements it is like driving a car as blind. Then the Smart Grid will do stupid decisions and actions.

Figure 3 shows the idea of how voltage and current monitoring can be seen as ears and eyes of Smart Grid in the low voltage network. As for person eyes and ears will give lots of information that are affecting to decisions and actions of that person. In the Smart Grid the AMI (with smart meters) could give majority of useful information from low voltage network. This information with information from other information sources (e.g. information from different voltage level, information about the weather) is then used in applications to make decisions how to control the network efficiently and finally actions and controls are made to achieve efficient use of a distribution network.

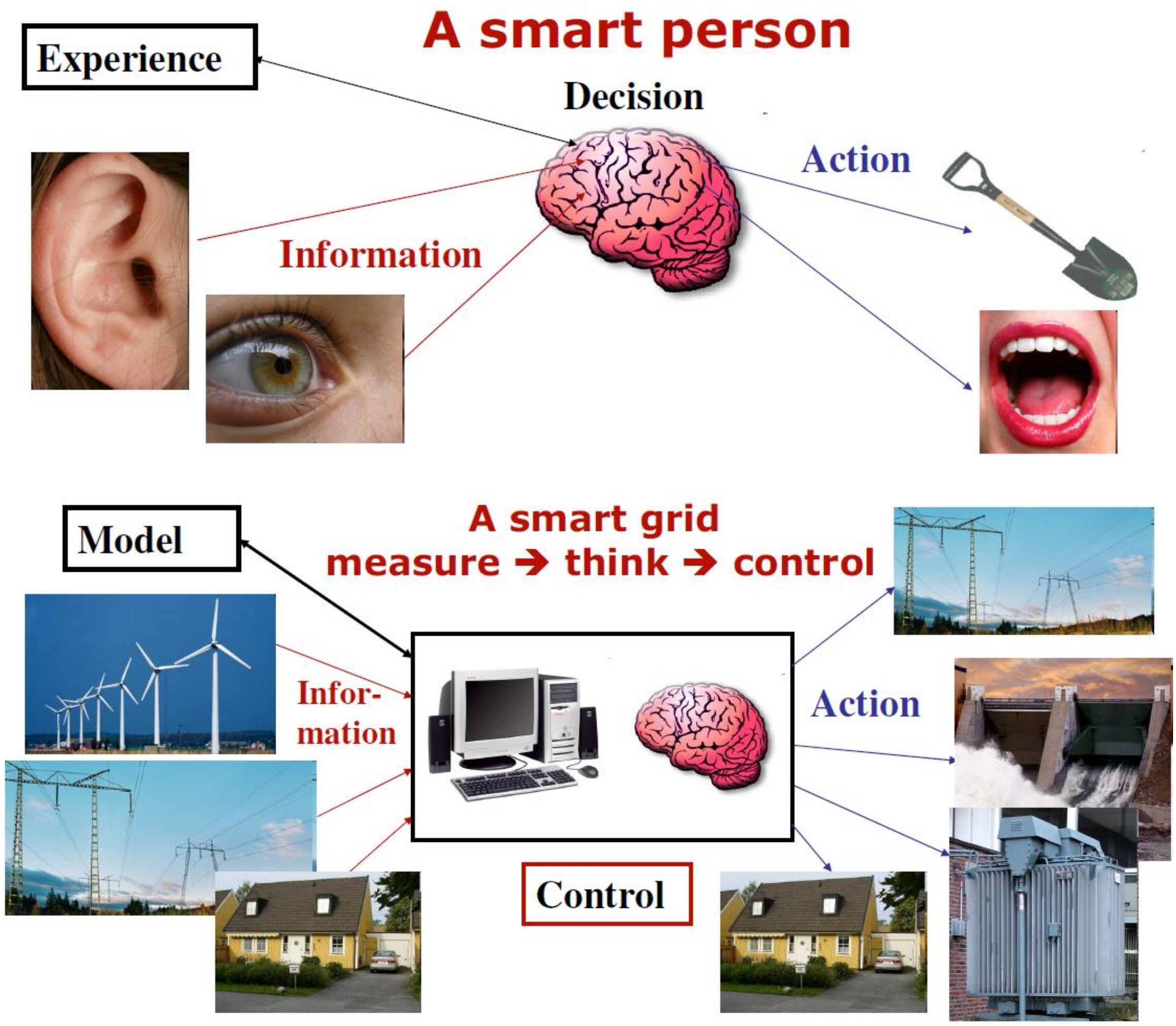

Figure 3. Smart Grid and smart person comparison.

STATE OF THE ART SMART GRID IN FINLAND COMPARED TO OTHER WORLD

In Finland the voltage monitoring has normally based on measurements in HV and MV level. Voltage level of low voltage networks has been estimated using MV voltage level measurements. Some utilities have used also Distribution Management System programs to estimate voltage level in low voltage networks. Outages in MV level have been recorded so that the number of MV/LV substation in outage region has been stored. Outages in low voltage level have been recorded so that the number of customers in outage region has been stored. Other power quality quantities have been monitored with case specific measurements.

The implementation of smart meters has changed this situation. Vattenfall was the first utility in Finland how decided to install smart meters to every customer. These meters are used to identify faults in low voltage level (zero conductor faults, one/two phase missing) and separate those from MV faults, to perform remote meter reading with hourly consumed energy data, to identify voltage unbalance and voltage level problems. Some of data is used in distribution network planning to identify places where network upgrades are needed. Nowadays full nationwide implementation of smart metering is on the way. The goal is that at least 80 % of all customers are equipped with remote reading energy meters by end of 2013. There are some minimum functional requirements such as: ability to remote readings, hourly interval measurement data of consumed energy read once in a day (data must be stored 6 years), registering start and end time of over 3 min outages (data must be stored 2 years), system must be able to receive/perform/send further demand response commands, and the data security must be in suitable level. Expect over 3 minute outages those minimum requirements are not covered with other power quality quantities. There are some pilot projects going on that include smart metering for distribution automation and in small scale spot price based control of electrically heated customers. In addition of Finland also in Sweden and Italy smart meters implementation is very far. [14, 15]

In Spain the Ministry of industry has established the official implementation plan for electrical residential customers. Metering equipments roll out has scheduled to stop by end of 2018. The effective implementation of AMM systems must be in running before first of January 2014. The main functional requirements for smart meters of residential customers called metering point type 5 (customers contracted power up to 15 kW) are: active and reactive registration in any direction, hourly active and reactive energy load profile (min 3 months data storage), register outages longer than 3 minutes and (exceeding) the limits of the nominal voltage allowed (remote power quality events), remote load control, up to 6 programmable registers, bi-directional communications, remote reading management, remote synchronization, rates remote programming, alarms and events registration and storage, the meter must store the last 3 billing periods and utility is in charge of programming the secret passwords. In power quality and voltage monitoring point of view requirements to register outages and voltage level are specified. In Spain Endesa has started the implementation of smart meters in the first half of 2010 [18] and the mass roll out should be ready to start by the end of 2010. The deployment to all 13 million customers will be completed in 2015. [15]

As a country UK seems to be behind Europe in terms of smart meter technology. In 2009 the Government has revealed its plans to roll out smart meters to all households by 2020. At the same time the Government confirmed proposals for high level functionality of smart meters for domestic sector. These high level smart meter functionalities are shown in table 2. Table 2 shows that these requirements are quite similar than all other smart grid requirements There are remote reading, two way communication, home are network based on open standards and protocols, support for tariffs, load management capability, remote disablement and enablement of supply, exported electricity measurement and capacity to communicate with a measurement device within microgenerator. [15, 16]

Table 2. Proposal for high level functionality of smart meter system [17]

	High level functionality	Electricity	Gas
A	Remote provision of accurate reads/information for defined time periods - delivery of information to customers, suppliers and other designated market organisation	✓	✓
B	Two way communications to the meter system - communications between the meter and energy supplier or other designated market organisation - upload and download data through a link to the wider area network, transfer data at defined periods, remote configuration and diagnostics, software and firmware changes	✓	✓
C	Home area network based on open standards and protocols - provide "real time" information to an in-home display - enable other devices to link to the meter system	✓	✓
D	Support for a range of time of use tariffs - multiple registers within the meter for billing purposes	✓	✓
E	Load management capability to deliver demand side management - ability to remotely control electricity load for more sophisticated control of devices in the home	✓	
F	Remote disablement and enablement of supply - that will support remote switching between credit and pre-pay	✓	✓
G	Exported electricity measurement - Measure net export	✓	
H	Capacity to communicate with a measurement device within a microgenerator - receive, store, communicate total generation for billing	✓	

Those requirements in table 2 are in very general level. In UK the Energy Networks Association (ENA) has given more detailed requirements that 1st generation smart meters should be able to perform. There are many detailed requirements in field of asset network performance, actively manage network / system balancing, actively manage network – planned & unplanned outages, manage safety issues and support network activities. There are also requirements for power quality issues. To point out power quality requirements those are gathered in to table 3. [18]

Table 3. 1st generation smart meter requirements for power quality issues made by Energy Networks Association [18]

DNO 04.04	The meter will be configurable to provide the average, max and min voltage during scheduled periods.	✓	
DNO 04.06	The meter will provide power quality readings as configured and on demand	✓	
DNO 04.11	The meter will store voltage profile data for 3 months	✓	
DNO 04.12	The meter will continuously store a specified minimum number of Under and Over voltage events	✓	
DNO 04.13	The meter will store a configurable minimum number of power quality readings.	✓	
DNO 04.15	The meter shall record Quality of Supply events.	✓	
DNO 04.01	The meter shall detect under voltage and over voltage levels.	✓	
DNO 04.08	Meter will issue an alarm when Over or Under voltage is detected	✓	

From other big EU countries in Germany a full national roll out is under discussion. In France EDRF expected to commit to a full roll out in 2010 based on results of trial. Target is that 96% of smart meters are installed by 2020. [15]

RESEARCH NEEDS

In this field there has been research. Some papers are focusing distribution system state estimation using AMI. One such paper is considering branch current based state estimation. This paper is not focusing voltage monitoring but is interesting because of AMI data use. [19] Some research are focusing open system approach. The main idea in these research are that some sort of standardization is needed that meters and applications, made by different vendors and applications operating in different phases of power quality measurements and analyzes, can share information. [20]

In Finland there has been research program called PiHa which is focusing management of low voltage network. Program focuses to integrate new generation AMR-meters (or AMI smart meters), telecommunications and distribution management systems to achieve low voltage management system as part of whole distribution management system in economic friendly way. One view of this program shows that power quality monitoring could be one part of applied AMR-level. The overall IT infrastructure of the pilot case of this program is presented in Figure 4. [21]

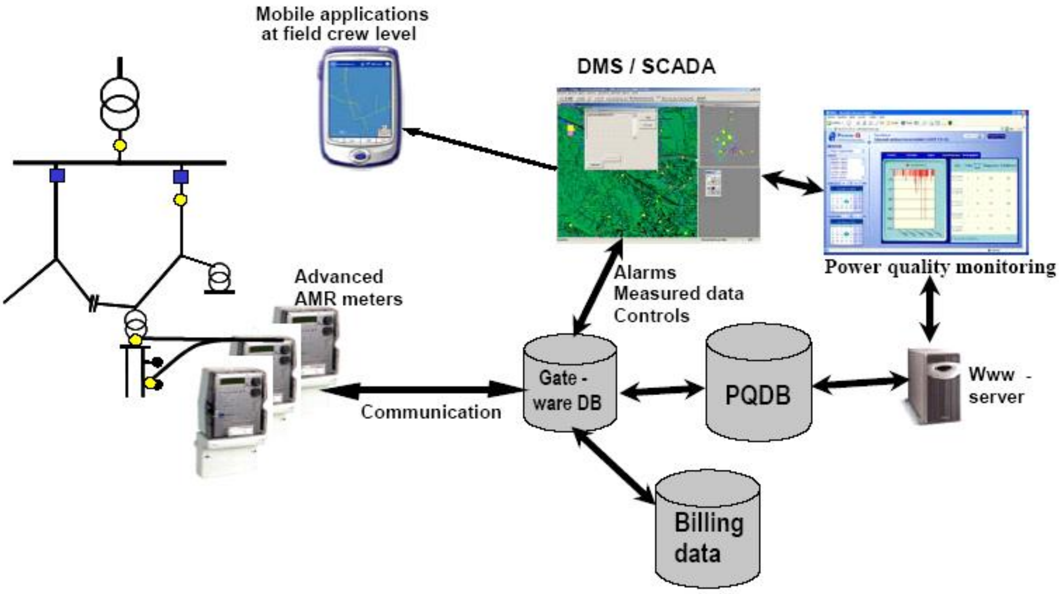

Fig.4. The overall view of IT architecture in the pilot case [21]

In addition of PiHa there has been also other research about use of internet in power quality monitoring. These other research has mainly focused in cases where the power quality data is formed with specific power quality meters from specific places not with AMI smart meters from every customer supply terminal. The idea is that power quality information could be provided through internet to power quality databases, different clients and even customers. [22] There are also papers that are discussing how to create regional power quality monitoring power quality monitoring system. One view about the structure of regional power quality monitoring system is shown in figure 5. In this view there are specific power quality meters in different places that are communicating with child station of collecting data with GPRS and data collection stations are connected to database server and to web server. [23]

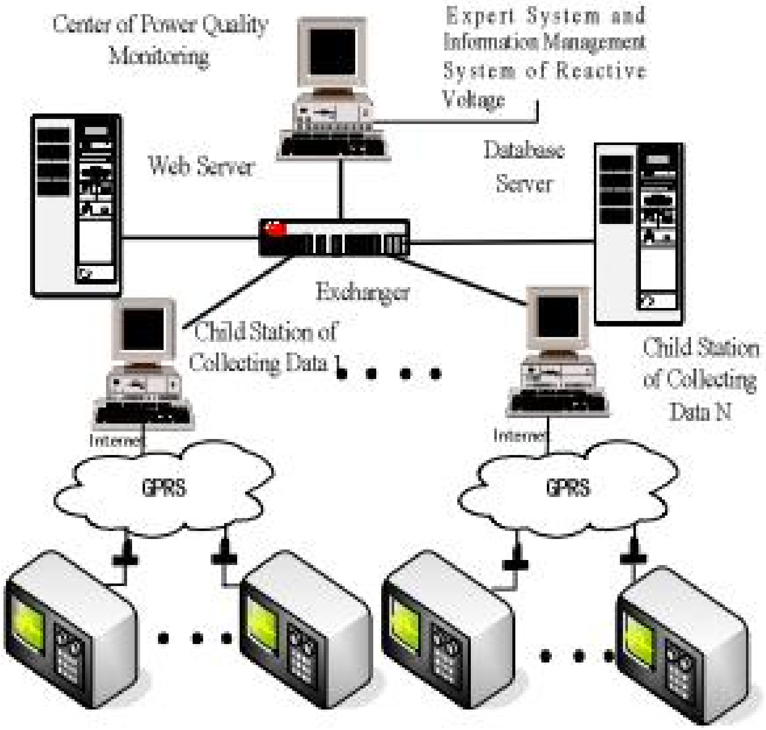

Figure 5. Structure of the regional power quality monitoring system. [23]

In addition of these system structures there are need for methods how to discover power quality disturbances in distribution networks. There are lots of methods in use today. Today's case specific measurement devices are using accurate measurements and highly advanced logics. One new kind of approach is to use wavelet transform based methods [24]. Other interesting approach is previous mentioned load signature method [12, 13]. These methods are quite accurate and will need accurate measurement devices.

Common thing to all accurate methods are that devices needed in these applications are still too expensive to use in extensive power quality monitoring systems. In the future these methods might be integrated into smart meters. To achieve economically ideal level in power quality monitoring it will need more research. One such research topic is what should be the measurement requirements of 2nd generation of smart meters to provide adequate power quality monitoring system. Also research is needed in field what is adequate power quality monitoring level and what is the relevance of each power quality quantities. For example, flicker definition is coming outdated because new compact fluorescent lamps have different flickering characteristics than incandescent lamps. One big area where research is needed is that what should be done with/to enormous amount of data to accomplish power quality monitoring when AMI is used in power quality monitoring. In addition of power quality monitoring there must be some abilities to affect to condition of power quality to reach the level of 21st century power quality. These abilities are one field where research is needed. Also measurement device development will be needed to ensure more accurate power quality monitoring system in the future.

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4. Low voltage network automation and management in Smart Grids

Author: Niklas Löf

INTRODUCTION – SMART GRIDS

Today the electricity is carried along a power grid that dates mostly back to the 20th century while it should meet the challenges of the 21st century, such as: growing energy demand; energy independency and security; greenhouse gas reduction; policy and regulation; technology advancement; infrastructure reliability and security; 21st century power quality. [1] These issues have set pressure for a change in electricity distribution and as a consequence a concept for future electricity network, Smart Grid, has received great interest, especially in the European Union (EU) [2] and in the United States (U.S.) [3] This modern electricity distribution system is supposed to be more flexible, secure, reliable and efficient than present system, and also has smaller environmental impacts [2, 3]. A more versatile list of benefits of Smart Grid has been published by the U.S. NIST (National Information Standards Institute). The most relevant benefits from the grid point of view are probably the following benefits:

- Provides a reliable power supply with less outage
- Self-healing capability due to use of digital information, automated control and condition based management
- Detection of unsafe and insecure events to secure the reliability of the grid
- Increased efficiency by reduction of total energy use, peak demand and energy losses
- Support for the integration of renewable energy sources and electric vehicles
- Reduction in the operation costs of the grid. [4]

Smart Grid can be seen as an intelligent network that effectively combines electricity network technologies that already exist or are under development together with ICT (Information and Communication Technologies), advanced distribution automation (ADA) and advanced metering infrastructure (AMI). [2] As it can be seen from Figure 1, which depicts a market forecast of the proportion of different technologies in the Smart Grid business in U.S., especially the role of ADA and AMI will be significant in the near future. AMI has been seen important especially in the integration of distributed generation (DG), load control and market-based demand side management (DSM), and in the development of active network management. [6]

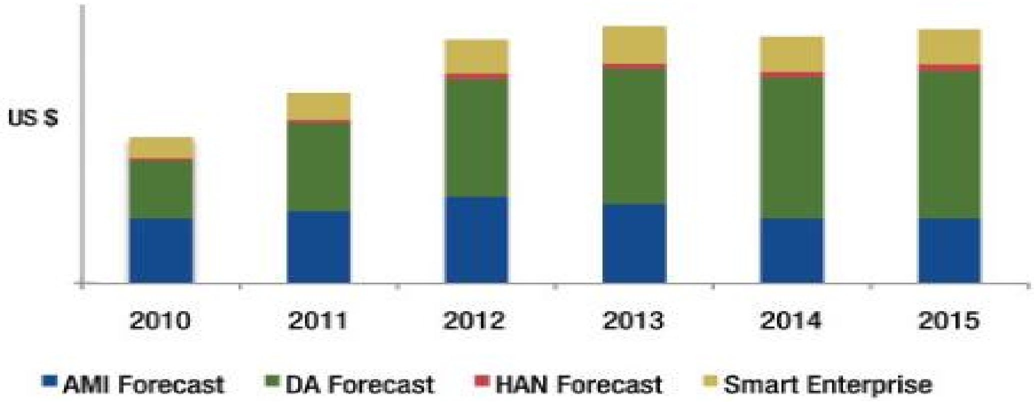

Figure 1. A market forecast of the Smart Grid business in U.S. [5]

The main difference between the present grid and the Smart Grid is that the last is a transformed electricity distribution network which uses two-way communications together with advanced intelligent technologies to improve the efficiency and reliability of power transmission and delivery. Proliferation of intelligence in electricity networks provides increased reliability and power quality; improved responsiveness; increased efficiency; management of current and future demand; potentially reduction in costs for provider and consumer; and communication platform for new applications. Intelligence is needed especially to manage increasing distributed energy production and other distributed energy resources (DER), such as energy storages, controllable loads and the charging of electric vehicles (EV). [1]

The development towards Smart Grids increases the importance of the LV network automation, which has traditionally been quite slight in electricity distribution. The role of the LV automation will be significant in Smart Grids due to advanced metering infrastructure, small scale distributed generation, and the charging of plug-in hybrid electric vehicles (PHEV) and full electric vehicles (EV). For these reasons the automation intensity level of the LV network needs to be increased in the near future. In practice this means that the management of the LV network is becoming increasingly important. [8]

LV NETWORK AUTOMATION AND ADVANCED METERING INFRASTRUCTURE (AMI)

Distribution network automation has traditionally been focused on the medium voltage (MV) network whereas the LV automation has got remarkably less attention, as the importance of it to the reliability of the distribution network is relatively small [7]. Distribution utilities have been averse to invest in LV automation, even though many different LV automation solutions are available in the market and some of them have been used in the industrial LV networks for years, such as circuit breakers. Probably the most major barrier for many automation solutions has probably been that large-scale installations of them in the public LV network have not appeared to be sensible investments in economic or technical terms. Therefore, so far these LV automation solutions have been used to improve the performance of the LV network case-specifically.

As mentioned, in the future the importance of LV automation is increasing. Due to tightening power quality requirements and increasing penetration of distributed generation (DG) there might be a need to replace fuse protection, which has still remained as the most common way to protect public LV networks against short circuits and overcurrents, with circuit breakers and relays. Voltage quality problems may increase in the future, because of increasing installations of big motor loads (e.g. heat pumps, airconditioners) in customer premises and increasing penetration of intermittent renewable DG production. Therefore more power electronics and LV automation solutions are needed to manage voltage level fluctuations. At the moment there are available in the market, for instance, MV/LV transformers that besides of fixed tap ratio are equipped with an active voltage regulation, which is controlled mechanically, magnetically or by power electronics. For instance, Voltage Booster, SmartTrafo and Intelligent Universal Transformer, are such transformers. [7]

In spite of all, in the near future the intensity level of distribution automation in the LV network is about to increase substantially especially due to advanced metering infrastructure (AMI) [7, 8], which has been seen as one of the most essential parts of the vision of Smart Grids. [2, 3] AMI is often referred to a trendy phrase “smart metering”, even though the meaning is not exactly the same. Smart metering actually deals with residential smart meters and metering systems related to them, whereas AMI is associated to an metering infrastructure that can provide information in real-time manner from every strategic point across the distribution network, not only from customer premises. Another definition of AMI could be that it refers to a system that measures, collects and analyzes energy usage and other measurements, and interacts with smart meters through various communication media [8].

The above definitions for AMI did not answer what it has to do with distribution automation. It is true that these two can be dealt separately as in Figure 1 for example, but in this paper AMI has been seen as a part of distribution automation. Reason for this is the definition of distribution automation given by the Institute of Electrical and Electronic Engineers (IEEE) in 1998:

"Distribution automation is a set of technologies that enable an electric utility to remotely monitor, coordinate and operate distribution components in a real-time mode from remote locations"

When AMI is integrated to present network management systems it can fulfill this definition completely. From LV network point of view AMI covers smart meters installed at customer connection points and MV/LV distribution substations, and also secondary substation monitoring systems too. The first major steps towards comprehensive AMI have already been taken, in particular, by virtue of the present proliferation and advancements of advanced automatic meter reading technology. [7] Remotely readable energy meter is being developed to be an intelligent device that, in addition to traditional energy metering, also includes different kinds of new advanced functions based on local intelligence [6].

Automatic meter reading (AMR) technology

The automatic reading of residential and industrial meters via a communication network has been a topic of discussion and research over decades. In 1965, Transitel Automatic Meter Reading System was trialed over a sixteen-month period in Michigan (U.S.). This test confirmed that the

AMR system for the reading of residential utility meters is technically feasible and throughly compatible with associated telephone company equipment and facilities. The test involved the reading of electricity and gas meters at individual home and apartment house locations. [9] However, as far as is known the first commercial automatic meter reading system was introduced at the end of the 1970's by Metretec Inc. [10]. In the 1980's, it was followed by many other similar systems, such as ABB DLC-M, RMS Power Net and MELKO. These first generation AMR systems were mainly used to gather information of energy consumption of large customers and in some cases for load control as well. [7]

Since those years rapid development in microprocessor technology has enabled to add versatile features to the meters more easily and with a relatively small cost. As a consequence in the 2000's the new generation of AMR systems was introduced, which made it feasible to install AMR meters to smaller customers too. Italian electricity distribution utility ENEL Distribuzione S.p.A. was the first utility worldwide to begin a large scale AMR implementation in 2001 and by 2006 ENEL had installed approximately 30 million AMR meters. [7] Nowadays advanced AMR meters have a significant amount of computing power and large amount of memory to store data compared to the old meters. Moreover, these meters can gather significant amount of information about the distribution network.

Recently published survey "Smart Metering in Western Europe" [11] estimates that from the total amount of approximately 250 million electricity meters in Europe, roughly 45 million AMR meters have been installed so far. Figure 2 illustrates the development of AMR meter installations in Europe during 2008-2014.

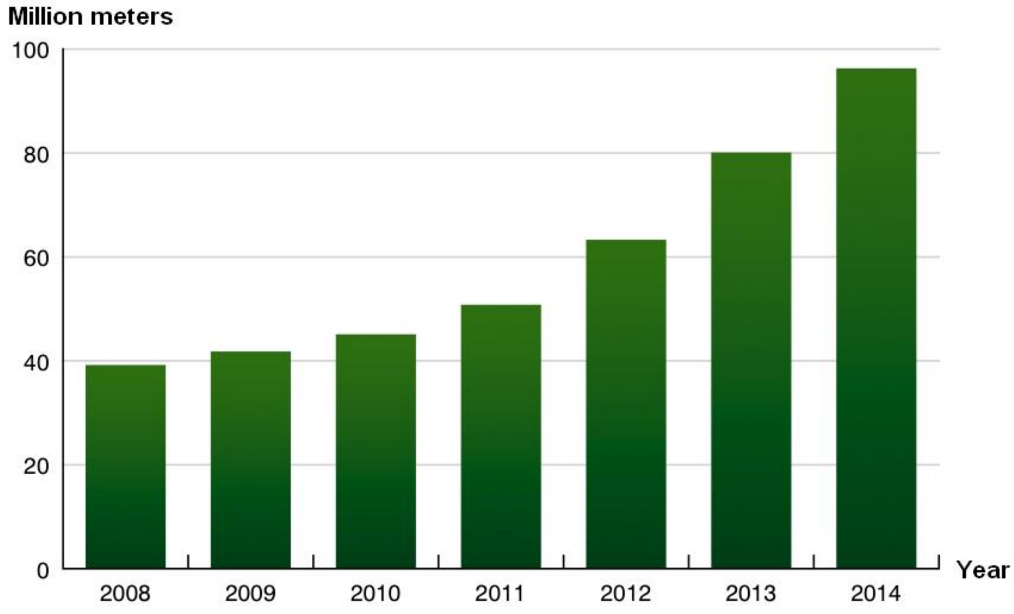

Figure 2. An estimation of the installations of AMR meters in Europe during 2008-2014. [11]

In the April 2009 European parliament voted for 3rd energy package, which commits member states to roll out smart meters to at least 80 % of customers by the end of the year 2020. Full penetration of smart meters in Europe should be achieved by the end of the year 2022. Driven largely by this energy package, and environmental agenda and Article 13 of the Energy Services Directive, a significant number of member states of European Union have taken major steps towards a full roll out of residential smart metering. In Italy, Finland, Great Britain, Spain and Greece national rollouts are underway, and in Sweden (approx. 5,2 million customers) smart meters are already completely deployed. However, many countries (e.g. Germany, Netherlands and Norway) still discuss about national roll outs and have not done any final regulatory decisions yet. Some countries, such as Romania and Cyprus, do not have any major plans for smart metering. [12]

Requirements for smart meters and metering systems vary from country to another, because of the lack of common minimum requirements. So far the legislation has been slow in Europe to react and produce generic and adequate requirements for smart metering that could meet the emerging needs of different countries, even though the development work of standards intended to make smart metering interoperable is underway in U.S. and Europe. To fasten the development of standardization European Commission issued the Mandate M/441 on development of an open architecture for utility meters to European standardization organizations CEN, CENELEC and ETSI in March 2009 [12, 13]. According to the European Regulator´s Group for Electricity and Gas (ERGEG) [14], in addition to those in the MID and as stated by the European Commission in M/441, the following additional requirements for the functionalities of smart meters have been identified in the ongoing work of M/441:

- Remote reading of produced and consumed energy
- Two-way communication
- Interval metering/registers
- Remote management (remote control/upgrade)
- Interface with the home automation
- Information trough webportal/gateway.

In the U.S. the NIST has presented a roadmap for Smart Grid interoperability that covers similar ground the Mandate M/441 for metering but also extends to a wider set of Smart Grid functions. [12]

As standardization work has been slow, many countries within European Union (e.g. Finland, the Netherlands, Spain, UK, France, Italy and Ireland) have introduced their own national requirements according to interfaces and functionality of smart metering systems. Outside Europe, at least Australia and Ontario in Canada have also their own national requirements. There are also many countries that have not yet defined any national requirements for smart metering systems or the requirements are very loose. For instance, in Sweden only national requirement for the meters is remote reading at least once in a month. [12, 13]

Secondary substation monitoring systems

Traditionally most of the MV/LV substations have not been monitored at all. In the secondary substations that have been under monitoring, it has been performed mostly temporarily and offline based on fixed local measurements of a certain monitoring device. The memory of these devices could then have been read afterwards (e.g. to a laptop via serial port) and analyzed later on. The remotely operated secondary substation monitoring systems have been uncommon, because the methods available for secondary substation remote operation, control and condition monitoring have not been as cost-effective as those available to primary substations. In the beginning of 2000's the cost of the remote operation equipments of MV/LV substation was still more than the cost of MV/LV substation itself. However, after those years the costs of MV/LV substation monitoring equipments and communication technology have decreased dramatically after that thanks to rapid technical deployment. [7]

The modern MV/LV substation monitoring devices are based on the technology used in protection relays [15]. For this reason modern MV/LV substation monitoring systems can offer versatile functionalities, even though, most of them aim to support MV fault management, such as indication of MV earth and short circuit faults. Nevertheless, these devices measure all electrical quantities on the LV side of the transformer, and can calculate the loading of the MV/LV transformer and register the abnormalities in power quality. All the measurements and state information can be stored with a time stamp, and they can be read remotely from the device whenever necessary. In the most critical situations (e.g. critical power quality abnormalities, transformer overloading) the modern secondary substation monitoring devices can send an alarm. [7, 15]

UTILIZING ADVANCED METERING INFRASTRUCTURE IN LV NETWORK MANAGEMENT

Distribution network management systems, such as DMS, SCADA, NIS/GIS, have been developed to serve mainly the MV network. By integrating advanced metering infrastructure (AMI) into present network management systems LV network management can be improved. [7] Two-way communication between utility and customer site make it possible to enlarge online monitoring to LV network. The use and integration of AMI to DMS can been seen as an extension of distribution automation and SCADA to the low voltage level. [16] As it can be seen from Figure 3, for example, advanced AMR meters can be utilized in many functions of distribution utility (i.e local DSO), e.g. to support network operation (e.g automatic LV-fault indication, isolation and location, precise voltage and load data), network planning and asset management (e.g. exact load profiles for network calculations), power quality monitoring (e.g interruptions, voltage abnormalities), customer service, and load control in addition to traditional use in billing and load settlement. [6] In addition, the integration of secondary substation monitoring system to SCADA and power quality systems can profit network operation, planning, maintenance, life cycle optimization, and power quality monitoring and fault analysis. It is a common practice in Finland to have network data available at NIS also from the LV network. Control centre information systems are also highly integrated, and therefore e.g. network and customer data are also available at DMS. [8]

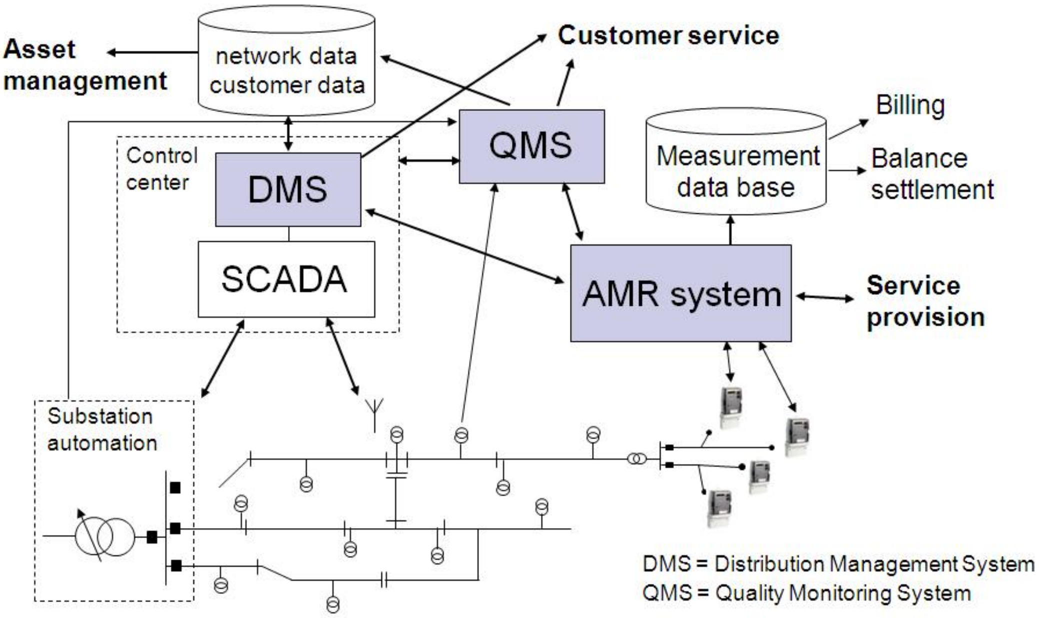

Figure 3. A vision of the utilization of AMI in comprehensive network management. [6]

This paper discusses how AMI data can comprehensively be utilized in LV network management. The aim is to provide a state-of-the-art of useful smart meter functionalities that can benefit network operation, planning and asset management. Figure 4 represents comprehensive approach for using AMI in LV network management discussed in later chapters.

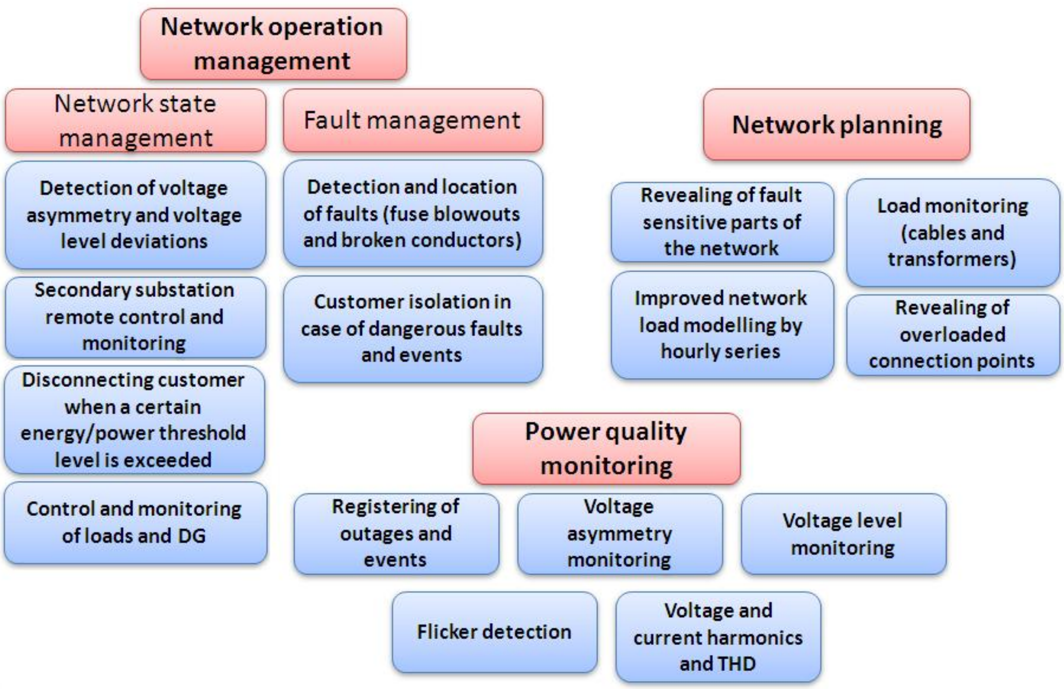

Figure. 4. Utilizing AMI in LV network management [8].

In some Finnish distribution companies comprehensive integrated information system entity for LV network management based on installation of advanced AMR meter has been realized, described in [16] and in [17]. The latter introduces installation of advanced AMR meters to all 350 000 customers of Vattenfall Distribution Oy in Finland where the system is in real operation. [8]

LV network operation management

Network operation requires information about the state of the distribution network all the time. This information should reach the control centre almost in real-time at least. Traditionally the real-time information has been available from the MV network only. Two-way communication between distribution network company (i.e. DNO) and customer site make it possible to enlarge online monitoring and control to the LV network. The use and integration of AMI to DMS can been seen as an extension of distribution automation and SCADA to the low voltage level. [16]

Fault management

Nowadays LV network faults are not detected until a customer makes a call to the control center that he/she is without electricity. Advanced AMR meters and modern secondary substation monitoring devices can both detect missing phase voltages and other voltage abnormalities, and then send automatically alarms about faults to the DMS system. The missing phase voltage information makes it possible to reveal fuse blowouts that can cause an outage to customers. Secondary substation monitoring devices, however, cannot detect blowouts of fuses located in LV distribution cabinets or broken LV conductors behind the fuses of the secondary substation. Instead, as the advanced AMR meters can cover every customer premise, only very few faults remain outside the advanced AMR system, that informs control center about faults in the LV network. Alarms cannot be sent when all phase voltages (e.g. 3-phases in Nordic Countries) are missing simultaneously, because the communication network could then jam in case of MV faults, as those are seen as an outage at the LV side. [16, 17] For the same reason meters that are connected to one phase only cannot send alarms about missing phase voltage at all. Nevertheless, advanced DMS can detect some of these faults with queries that can be sent to the meters [4]. Queries can be extremely useful when a MV line have been repaired and re-energized after a major disturbance. With queries the control centre can detect the broken LV lines and send the field crew to repair the LV side before they leave the faulted area [8].

Another important benefit is improved electrical safety as advanced AMR meters can detect voltage abnormalities (e.g. voltage asymmetry, under and over voltages) and based on the voltage asymmetry information it can detect a broken neutral conductor. An advanced AMR meter equipped with a specific disconnection unit can then isolate the customer automatically from the LV network in the case of a dangerous event or fault. Customer isolation is important especially when a neutral conductor is broken in the LV network, because in that case hazardous voltages can occur, which can damage electric devices and cause a fire. In the worst case the metal covers of electrical devices become live and therefore dangerous to people around them [16, 17].

Advanced AMR meters can also gather valuable information about interruptions, such as fault type, the beginning and ending time of fault. The interruption information can be gathered automatically, which can make the interruption reporting regarding LV faults more fluent. The system can also distinguish all interruptions that have been borne in the LV network from the MV interruptions. So far LV interruption reporting has been done manually and the interruption durations have been rough estimations, as there has not been realiable information about the beginning times of interruptions. AMR also improves the quality and plausability of interruption indices used in regulation. In Finland, for example, the determination of compensations in long interruptions can be automated using AMR data. [7, 16]

Network state management

Network state management is defined here as remote and automatic actions that are used to achieve the most optimal use of the network. Today the control activities done in the LV network are performed mostly to balance the peak demand of the power system by controlling particular loads (e.g. electric space heating on/off) of a customer on request or the basis of pre-defined schedule. In addition to traditional load control, advanced AMR meters equipped with an available programmable relay output can enable more advanced control functionalities, such as demand side management and frequency depend load shedding. Nevertheless, these functionalities actually support network management more at the higher level of the power system than at the LV network level. [8]

From the LV network point of view it could be more valuable to control loads to protect network assets from overloading. Momentary overloading of LV assets is possible because the characteristics of the fuse protection allow the exceeding of nominal current for some time without causing a blowout. The overloading can decrease the remaining lifetime of the assets or even damage them. [8]

AMI can enable various load controlling functionalities. These functionalities can be performed automatically or remotely from the control centre depending on the measurements that are available. If the measurements are gained from residential smart meters only, the control centre could receive an alarm about distribution transformer overloading, and preplanned changes in the LV network state might be performed. When the measurents are available from the secondary substation the customer loads could be controlled automatically with an intelligent device from the secondary substation and an alarm is sent to the control centre only, if the automatic control fails. The latter functionality can be extremely important in the future, if the charging of electric vehicles becomes more common, as it can be utilizied in smart charging. This functionality also increases the self-healing of the distribution network, as with intelligent customer load control the fuse blowouts at the LV feeders could be avoided. [8]

At the customer level automatic load control is necessary. In fact in advanced AMR meters certain power limits can be set and when the power consumption in customer connection point exceeds the pre-programmed threshold value the meter can automatically control particular loads of the customer. [8]

In addition to above mentioned control functionalities, in advanced AMR systems the remote disconnection of a DG unit in case of maintenance or fault repairing work can be enabled with eters equipped with a disconnection unit. The disconnection can be done also automatically, which could be useful in a case of loss-of-mains. Nevertheless, disconnection units at present are not able to break fault currents. [8]

LV asset management and network planning

The LV network may not have been as critical part of the distribution network from the reliability point of view as the MV network has, but its importance from the viewpoint of network assets is evident. The LV network is the most extensive and expensive part of the distribution network. For instance, in Finland the LV network comprises over 60 % of the length of the distribution network and approximately half of the total value of the distribution networks is committed in LV networks (including MV/LV substations) [18]. Moreover, the most of the network losses in electricity distribution are occurred in LV networks and in secondary substations that are feeding them.

Traditionally the evaluation of the state of the LV network has been based on network calculation, computed value of short circuit current and possible power quality reclamations [19]. The AMI system can provide accurately metered data, which can be used to improve the accuracy of network calculations, and to provide new tools for power quality and load analyses. [8]

Improved network calculations

The initial information for network calculations (i.e. power flow and fault current calculations) is obtained from the network database (e.g. network topology and component properties) and from the customer database (e.g. load curves). One of the most challenging issues regarding network calculations of the LV network is the fact that the smaller the amount of customers examined in statistical network calculations the more inaccurate are the results. [8]

The hourly series data obtained from advanced AMR meters can be used to improve load modeling, thus giving more accurate results in LV network calculations. However, instead of replacing the load curves directly with hourly series in network planning, AMR data should be used to refine the present customer classification/clustering and load curves. Recent studies have proven that direct replacement actually do not increase the accuracy of load flow calculation results, but can make them even more inaccurate. Advanced AMR meters can also provide hourly series of reactive power to improve the results. In network calculations it is usually assumed that the power factor is constant. In the reality the proportion of real and reactive power varies all the time. [8]

With improved network calculations the peak demand, which is the most important planning criteria, in each point of the LV network can be estimated more accurately. In practice this means that the dimensioning of LV network components and fuse protection can be optimized. In addition, the losses can be evaluated more precisely. [8]

Novel network analyzing tools based on AMI data

In reference [20] novel network planning and asset management supportive analyzing tools based on AMR data were examined. These tools enable to analyze the loading of network components (e.g. distribution transformer, cables, etc.) or even to make direct conclusions about the network state, such as the criticality of network renewal.

Traditionally LV networks have been designed in such a way that overloading can be avoided and there is left some capacity margin for future load increment. However, the consumption habits of customers can change temporarily or permanently. Customers can invest on electricity based heating or cooling systems in an area where such a systems have been uncommon before, which can remarkably increase the peak demand in the LV network. From the AMI data the increased peak demand can be indicated, and possible network reinforcements in the LV network (e.g. replacing the transformer or cables with bigger ones) can be done in time. Respectively the same information may be used to securely postpone network investments when peak demand has decreased (e.g. electrical heating has been replaced with other energy sources). [8]

From the AMR data it is even possible to reveal overloaded customer connection points. Despite the occasional appearance, overloaded customer connection points can be troublesome for DNOs. The detection of these kinds of problems is hard and time consuming today, as it requires additional resources for separate metering and local studying of the LV network. Instead, this process could be done automatically by an application that compares measured currents gathered from AMR meters to the fuse size information of the customer information system (CIS). [7, 8, 20]

Advanced AMR meters can also provide outage information that can be utilized to reveal fault sensitive parts of the LV network. By comparing this information together with other information (e.g. condition information, and manufacturing and vegetation clearing year of the line) renewal activities of the line and clearing activities of an electricity line right-of-way could be allocated more effectively. [7, 8, 20]

Voltage quality management in the LV network

Traditionally the voltage quality in the LV network is evaluated mostly based on the computational voltage drop, calculated value of short-circuit current, and to some case-specific measurements that have been performed when a customer have complained about bad voltage quality. Recent studies [20] have, however, shown that the first two values of the above mentioned indicators are not necessarily the best possible for voltage quality problems.

Advanced AMR meters have created an opportunity to expand the voltage quality monitoring to cover every customer premise. Depending on the meter configuration these meters can monitor some basic power quality quantities, such as voltage level in each phase and voltage asymmetry. Meters also gather voltage information that can be used to provide an educated indication about flicker, which is one of the most common reasons for the voltage quality complaints today. In advanced AMR meters there is also a possibility to set certain limits to these quantities, and when a set threshold level is exceeded, the meter can send an alarm about bad voltage quality. [8]

In addition to advanced AMR meters, there are also other smart meters that are capable to voltage quality monitoring, such as secondary substation monitoring devices. These devices can monitor a few voltage quality quantities that advanced AMR meters cannot (e.g. voltage harmonics), record disturbance events and in general are more accurate. The device can send an alarm about the most critical nonconformities in voltage quality whereas the less critical data related to voltage quality can be stored in a separate power quality database [15]. Furthermore, for the most critical customers specific voltage quality monitoring devices can be used. These devices are typically fixed installed. The devices can measure, for example, flicker, voltage dips and total harmonic distortion and can also send an alarm when necessary.

Even though advanced AMR meters do not necessarily include as versatile voltage quality measurements as above mentioned sophisticated smart meters, the coverage of these meters makes a comprehensive voltage quality monitoring possible. Voltage quality monitoring at the MV/LV substation level might give a good overall picture of voltage quality, but it does not provide any information about the voltage quality in customer premises where the standard EN 50160 states that the voltage quality should be measured. Moreover, the devices with more versatile voltage quality features have not proven to be installed to every customer, because of economical reasons and the fact that the AMR meter is installed there anyway. [8]

The voltage quality obtained from advanced AMR meters enables proactive voltage quality management, as the possible voltage quality problems could be detected and repaired before the customer notices it. Potential voltage quality problems can be plotted beforehand, for instance, by combining voltage quality measurements to calculational short circuit current value. In addition, in a case of customer complain the AMR meter data can provide valuable information about the voltage quality history from the customer connection point to customer service. [18]

RESEARCH NEEDS

Smart meters can provide lots of information about the distribution network that has not been available before. As the massive installations of residential smart meters are underway in many utilities in Europe and U.S., advanced metering infrastructure is extremely topical research area at the moment. According to ESMA [12], most of the projects these days in Europe are focused on demand response and the impact of smart metering on consumer behavior and how could they provide energy savings. Nevertheless, the comprehensive concept of using AMR system and data in network management has not seen as much research so far [16].

In Finland this area has been studied since a development project for comprehensive LV network management (PiHa – Pienjänniteverkon Hallinta) that was performed during years 2006 and 2007 in a middle size Finnish distribution utility, Koillis-Satakunnan Sähkö Oy (approx. 15 000 customers), together with device and system vendors (i.e. ABB oy, Aidon Oy, MX Electrix Oy, PowerQ Oy), and research organization (i.e. Tampere University of Technology). The developed solution for comprehensive LV network management was based on the integration of new-generation AMR system, ICT solutions and distribution management system (DMS), and it was tested with real equipments and systems. The integration provided multiple new features to DMS, which made it possible to extend distribution network monitoring from the MV network to the LV side first time in a cost-effective manner. [16] Later on the work started in the PiHa project has been continued and broaden the definition of comprehensive LV network management in the INCA

(INteractive Customer gAteway) project [19] that was performed between the years 2008 and 2010.

Similar activities have also been studied in another Finnish utility called Vattenfall Verkko Oy (approx 390 000 customers), which was probably the first utility worldwide who accomplished the implementation of advanced AMR system and DMS in a wide-scale. During 2009 the utility updated all their AMR meters and DMS to support LV network monitoring and the overall system was tested [17]. The novel DMS has now been in use since February 2010. The current trend in Finland seems to be that many other utilities are also interested in implementing similar kinds of functionalities in their meters. In addition to utilizing of AMR data in network operation, Vattenfall has also been actively investigating the possibilities to utilize AMR data in network planning [6]. Moreover, in 2008 another Finnish utility Helen in cooperation with different equipment and system vendors (i.e. VAMP Ltd., Netcontrol Oy, PowerQ Oy) carried out a development project on comprehensive secondary substation monitoring system [15].

In addition to Finnish activities, there has been some LV network management related research elsewhere too, but not in the same extent. Italian distribution utility ENEL (approx. 30 000 000 customers) has been developing novel applications, which are utilizing advanced metering infrastructure, for network optimization purposes [21]. In the paper [21] the following applications were discussed: distribution transformer utilization, power line loading, LV network energy balance and LV quality assessment. In Austria, a distribution utility called Energie AG oÖ Netz GmbH (approx. 430 000 customers), has also been studying the features of AMR meters, which could be utilized in LV network management. Together with other contributors they have applied a simple method to provide weekly basic statistical information about voltage levels at customer premises that can be utilized in the planning of LV networks. [22]

As the field of study is relatively new, many things regarding LV network management still needs to be solved. One of the biggest challenges in the future what comes to comprehensive LV network management is the increasing amount of information. Smart metering will increase the number of monitored nodes in distribution network significantly. Present ICT systems that are in use are mainly based on centralized data management, which in practice means that they are not anymore sufficient enough. When AMI is integrated to present network management systems the whole ICT system architecture from the device level up to the system level needs careful rethinking. Novel ICT solutions for these kinds of purposes are under development, for instance in a EU funded project called Integris (Intelligent Grid Sensor Networks) [23].

Novel and flexible ICT infrastructures could bring LV network management to a brand new level as it makes possible to improve existing applications and also it can enable studying of new applications. One such an existing application that could be improved is LV fault management application in DMS. Nowadays DMS cannot receive any outage alarms when all phase voltages are missing (i.e. in Northern Europe all three phases and in Southern Europe one phase), because that could cause the congestion of communication in a case of MV outage when hundreds of smart meters send alarms. New LV applications that could be studied more deeply from the LV network operation viewpoint could be, for instance, the real-time monitoring and management of the LV network state (especially in the LV networks with large amount of interconnected DG), and advanced load control applications (e.g. smart charging of electric vehicles). An interface from a smart meter to a home automation system could make these functionalities even more sophisticated. Therefore, it the integration of home automation with AMI could also be one interesting research issue.

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5. Business models to analyze implementation of Advanced Metering Infrastructure

Author: Petri Trygg

INTRODUCTION

Energy metering is facing significant challenges at the moment. Traditionally energy meters readings have been conducted once a year manually on site. At the moment many countries in the EU area are implementing new generation of advanced meters. Multiple registers, integrations and new features makes this investment a good platform to develop existing business and in some cases even totally new.

Advanced Metering Infrastructure (AMI) is primarily the physical tool for creating efficient electricity market for the end customer. Secondarily it helps to provide some of the information needed to operate future electricity grids also called as smart grids.

In many countries metering is responsibility of distribution companies. Distribution companies perspective with metering responsibility is taken as a view for this study. But factors possibly changing this have been taken into a count.

This study describes first the legal and regulatory framework that guides the development of AMI. As most of the regulatory issues and details are country specific the framework is searched from more general energy related legislation. On European level this is the 20-20-20 target.

The AMI concept is being analyzed by using business model concept. As it is much used and very few times defined concept the theoretical background is first explained. Then AMI concept is being presented using it on general level.

The business model concept is used to conceptualize and standardize the concept of AMI. The idea is to provide better understanding for the issue and things that may cause pressure to change it.

Advanced energy metering and terms used

New type of remotely read energy meters are under discussion. At least following terms are presented in discussions and presentations held:

AMR	Automated Meter Reading
AMM	Automated Meter Management
AMI	Advanced Metering Infrastructure

Additionally term Smart Metering is presented specially related to smart grids.

AMI INVESTMENTS IN EUROPE

Generally legal and regulatory drivers for AMI are country specific. Also the details related to organizing metering functions may vary in different countries. For this reason it is most reasonable to take the drivers with longer and more general impact. Climate change and environmental issues are in many cases the most significant global issues pushing advanced metering and secondary smart girds.

Actual processes for creating laws trying to push implementing advanced metering were made in 2007. The European leaders announced climate and energy targets to be met by 2020. These are also known 20-20-20 targets and they include [EUC10]:

1. A reduction in EU greenhouse gas emissions of at least 20% below 1990 levels
2. 20% of EU energy consumption to come from renewable resources
3. A 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.

In January 2008 the European Commission proposed binding legislation to implement the 20-20-20 targets. This ‘climate and energy package’ was agreed by the European Parliament and Council in December 2008 and became law in June 2009. [EUC10]:

More detailed following obligations have been set to member states [Str10]:

1. “Provide for the possibility of using energy efficiency and demand side management as alternatives to new supply and for environmental protection” Energy end use efficiency and energy services directive 2005
2. “Member States shall ensure the implementation of intelligent metering systems – subject to an economic assessment” 2006/32/EC2006/32/EC Article 13 & 3rd Energy Package
3. “ The consumer should be provided with information on actual consumption often enough to enable customer to regulate his own energy consumption” 2006/32/EC2006/32/EC

The European Union is the most advanced markets in terms of implemting AMI.

In Europe most of the western countries have AMI installed in majority of the customers by 2015.

In table 1 Sweden and Italy have completed their first full scale AMI implementations. Finland is following by 1.1.2014 with minimum 80 % installed and this is required by the regulation. Norway is following and AMI is at the moment under discussion. Central European countries are moving towards implementation excluding Germany. Also Netherlands, Portugal and Spain have postponed the implementation.

Table 1. Status of AMM in some of the European countries[Str10]:

Country	Status
Sweden	Completed
Italy	Completed
Finland	80 % by 1.1.2014
Norway	2015
Denmark	Discussion
UK	Mandatory
France	2012-2017
Spain	2018
Austria	Discussion
Belgium	Discussion
Germany	Postponed
Netherlands	Postponed
Portugal	Postponed
Greece	Postponed

Figure1. Status of AMM in some of the European countries[Str10].

CONCEPTUALIZING BUSINESS AROUND AMI

Concept of business model

Business mode concept has created a lot of discussions in business research. A common conceptual base is still lacking. But some parts of definitions seems to collect common understanding and this may lead to larger consolidation amongst scientists.[ZoAm10].

Looking at published definitions of the concept of Business Model (BM) it is obvious that concept has many different interpretations. According to [AmZo01] BM is a description on who is doing what to generate value. Value is also among the things to be defined. Their description states that business model is a value network and it describes how the network participants act. Another network based interpretation is presented by [FaBa03]. They see BM as means for business network to produce value with different technological means. Their perspective is to define what is the role of a single company in the value creating business network. [Mah00] has stated that it defines three essential flows in between of business partners and customers: value, logistic and earnings. [Mag02] defines it as a story that tells how the company is operating. The interaction between business process and BM is being discussed by [PeKi01]. They see that BM explains why the business processes are designed as they are. Also the interaction with BM and company’s strategy is one of the definitions by [RaRo01]. Their interpretation is that BM expresses the strategy of a company. This expression includes product strategy and models for service logistics and earnings. According to [Tim98] BM is architecture and income description of product, service and flow of information. He highlights the relationships, interactions and structures of different business parties.

In[Ost04] a single reference model is proposed based on the similarities of a wide range of business model conceptualizations. With this business model design template, business model can easily be described. It includes four main categories and nice building blocks:

1. Infrastructure

- Key Activities: The activities necessary to execute a company's business model.
- Key Resources: The resources that are necessary to create value for the customer.
- Partner Network: The business alliances which complement other aspects of the business model.

2. Offering

- Value Proposition: The products and services a business offers. [Ost04] describes value proposition is an overall view of .products and services that together represent value for a specific customer segment. It describes the way a firm differentiates itself from its competitors and is the reason why customers buy from a certain firm and not from another.

3. Customers

- o Customer Segments: The target audience for a business' products and services.
- o Channels: The means by which a company delivers products and services to customers. This includes the company's marketing and distribution strategy.
- o Customer Relationship: The links a company establishes between itself and its different customer segments. The process of managing customer relationships is referred to as customer relationship management.

4. Finances

- o Cost Structure: The monetary consequences of the means employed in the business model. Defines costs.
- o Revenue Streams: The way a company makes money through a variety of revenue flows. Defines income.

Business model describes how the company is operating to create value to the customer. Metering and ancillary services related to that are traditionally supporting functions related to billing. Additionally the final value created to the end customer is relatively small. It can be seen as counter that the bill is based.

Factors causing changes in business model

Time and it´s affect to business model not discussed much in literacy. Business model is typically seen as a snapshot[OsPi05]. [Ham00] and [LiCa00] discuss that business models change and this creates a need for more conceptual and shared way of describing them. They also state that in some cases companies use business models as a goal that they are trying to reach. [LiCa00] categorizes these into four models: realization, renewal, extension and journey models.

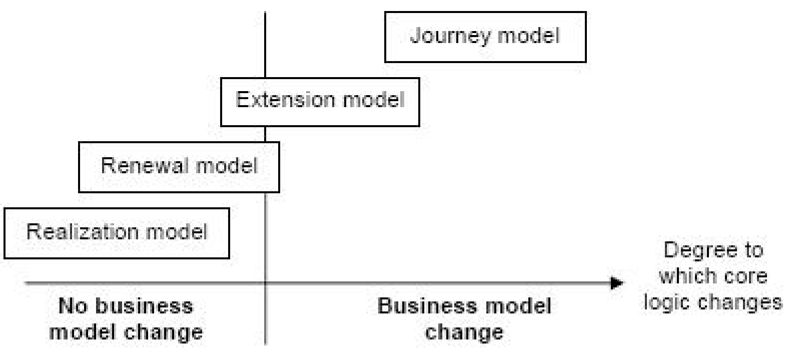

Figure 2. business model types in change[LiCa00].

On Journey model the changes are most radical and most of the 9 basic building blocks should be affected. On extension model some parts of the model remain the same but majority is to be renewed. On renewal model only some blocks are changed. Realization model is actually a description of existing business model.

(Ost04) and (OsPi05) defines the factors causing constant change from outside to following (currently and in near future):

- Technological change: How the latest technology is made to serve the company best?
- Competitive forces: How to best adopt to current competition situation?
- Customer demands: What the customers want and what are the trends?
- Social environment (ethics, values etc) : How doe the customers react to the values and ethics of the business ?
- Legal environment :What legal, tax and other barrier factors can cause to the value to the customer ?

Anyone partly responsible of the business model should constantly monitor and identify possible factors changing the business model. [Laa05] describes that technological changes may be the most important and cause significant changes to competition and market offering. Also according to [Laa05] this is caused by the fact that many companies are not doing enough innovations as they concentrate on doing incremental improvements. This results that present strategies repeat themselves. Business model changing is not taken into a count enough by the strategy in many companies.

Definition of AMI business model

In Metering business model the resources are being collected together. The resources are divided into information systems, Employees and hardware. The business model is in traditional model connected tightly to the billing and secondary to the customer service.

The final value creation to the end customer is described in business processes. This describes how the resources are being used. For example the yearly meter reading business process is done by meter readers once in a year.

Following listing is general and very short description of examples that would be included in the AMI business model framework of distribution company:

<u>1.Infrastructure</u>

- o Key Activities: The activities necessary to execute a company's business model.
    a. Distribution tariffs including possible tariff for customers own production.
    b. Billing and customer service related to that
    c. Technical support for different customer segments

d. Online and Extranet services

e. Home automation interfaces and services

- Key Resources: The resources that are necessary to create value for the customer.

  a. Meters

  b. IT systems and their interfaces/ integrations (Own or service -> reflects to the need of employees). Good example of some problems faced and things to look carefully are found at [ToTr06]. [ToTr06] also points out the interaction between employees and IT. This interaction and dependence should be considered as one of the critical factors on company's resources.

  c. Employees in terms of know-how and resources (may reflect to the needs of IT systems, working human resources management may be needed)

  d. Work management and general management in company

- Partner Network: The business alliances which complement other aspects of the business model.

  a. Metering service provider

  b. Field maintenance company installing and replacing meters

  c. Telecommunications provider

  d. Different IT systems providers

2. Offering

- Value Proposition: The products and services a business offers. [Ost04] describes value proposition is an overall view of .products and services that together represent value for a specific customer segment. It describes the way a firm differentiates itself from its competitors and is the reason why customers buy from a certain firm and not from another.

  a. Main offerering is the distribution of electricity in framework of sufficient power quality and reasonable price set by regulation.

  b. Secondary offering is customer service using different medias and resources

  c. Thirdly legislation and recommendations require that distribution company connects customers production unit into network and purchases the electricity (In Finland in future with feeding tariff).

  d. Additional offerings are control and reporting services and in future their expansion to integrate metering into home automation for load control and charging of electrical vehicles.

3. Customers

- Customer Segments: The target audience for a business' products and services.
  a. Industrial customers, for example users with fuse size over 63A
  b. Consumer customers, for example fuse sige 63 A and below
  c. Customers who have production, for example own wind generator
  d. Customers who have special need for example related to power quality, for example health care industry
- Channels: The means by which a company delivers products and services to customers. This includes the company's marketing and distribution strategy.
  a. The main channel is the Electricity network: the capacity, quality and price of electricity. Also ability to work with customers devices and production.
  b. Other supporting type of channels are Company website, extranet services, brochures, customer journals, bills, phone services company provides, meter display, home automation solutions interfaces, email services, normal customer service for example for billing, technical customer service etc.
- Customer Relationship: The links a company establishes between itself and its different customer segments. The process of managing customer relationships is referred to as customer relationship management.
  a. Industrial customers: Extended Online service, personal contact to someone in technical customer service
  b. Consulmer customers: Online with billing information, customer service for billing, meter display, customer journal, simplified bill

4. Finances

- Cost structure of automated meter reading is published in [TrKu05] and [TrKu07]. Activity based costing is used to compare traditional and automated meter reading. The method used requires work but can provide accurate data of resources needed for different business processes. Additionally [Ene07] is an estimation that AMM costs around 15-25 € per household in a year depending on the network area and AMM solution. More detailed the cost covers:

a. Meters 40 – 55 %
b. Additional equipment to meters such as breakers 5-25%
c. Installation and maintenance 10-25 %
d. AMM software 5-10%
e. Communication 5-40%
f. Training and development 1-3%
g. Other costs 1-10%

- Revenues of AMI for distribution system operators are[KäKo06]:
  a. Load optimization to replace network investments
  b. Fault detection and faster fault clearing to reduce outage compensations
  c. Billing of consumption and production
  d. Better calculation of losses
  e. Possibility to recognize some Power quality problems
  f. End of non scheduled manual readings etc when people move
- Revenues of AMI for the end customers are[KäKo06]:
  a. Faster customer service
  b. Possibility to save energy on peak price hours (Only if tariff causes peak prices and demand side management is possible)
  c. Possibility to have more accurate data on consumption (required for examply in EU by the 20-20-20 target)
  d. Different kind of billing options
- Revenues of AMI for energy sales companies [KäKo06]:
  a. Real time knowledge of the actual consumption
  b. Limit the uncertainty of type curve calculations
  c. Possibility for better optimization of purchases in electricity exchange
  d. Renunciation of the balance calculation (no more needed)

The revenues can be direct so that they appear only by setting up the AMI. In some cases to gain the revenues additional work is needed and in some cases AMI must be integrated to other systems to support different business processes. Examples of these indirect revenues from distribution system operators are load optimization, losses and power quality issues.

Business model final localization and details must be viewed with the understanding if the business model is intended to be Journey, Extension, Renewal or Realization model. Also company specific details with strategy related for example to IT must be taken into a count. Some companies prefer purchasing services also on IT and others want to keep IT in house.

Identification of factors that may cause changes to business models

Energy business is under pressure of changes. Many factors demand development and metering related functions in distribution companies are involved majority of development issues. Looking at table 2 it seems that many of the drivers for change have several categories they fit. Also many of them seem to have at least some kind of legal background. This causes that they are most likely to take place.

DISCUSSION

The European Union area will be in the end of this decade the leading electricity market area with Advanced Metering Infrastructure (AMI). This creates possibility for highly developed electricity markets and in some extends smart grids.

To understand the implementation of AMI, business model makes all the details more conceptualized. This helps to understand how the value to the end customer is created. Also identifying the possible change factors can guide the development and implementation of AMI.

Many things are currently pushing the AMI for majority of customers in Europe. The 20-20-20 target and laws and recommendations followed by it create need for distribution companies to develop their business model accordingly. This is not an easy task. Electricity distribution is highly information system intensive business and the change affects majority of them. This results also that the work employees do using them changes.

Implementing AMI in large requires also changes to the utilities IT systems. Interfaces and data exchange are required to enable the possibilities. This results that also the work done in utilities needs to change. More and new type of know-how is needed. This may require training of employees. Some of the benefits that AMI makes possible can be achieved only by implementing. Others are more indirect and may require designing special business processes. These can be issues like asset optimization and power quality.

Business model has also time relation. It can be created do describe the current situation as well as the situation company is heading for. Constant updating and following requires also identification of possible change factors. Factors like technological change, competitive forces, customer demands, social environment (ethics, values etc) and legal environment can create need for changing the business model to keep the competitive advantage or create more of it. This is task that management in the utilities should also recognize.

Table 2. Identified of possible factors that cause or may cause change in way AMI business model works.

Change factor	Actual changes
1. Technological change	o Interface with smart home control center for control and reporting o Need to be able to manage distributed generation better o Need for large scale load management / demand side management o Additional values and functionalities for customer service, network operation and asset management o New online and extranet reporting services
2. Competitive forces	o Regulation sets minimum level of requirements that AMI must be able to do o Development of service business and companies' strategy on using services instead of in house operations. o Development of energy sales(products, market players) will require more automation and capacity on handling customer events
3. Customer demands	o Home automation o Loading of electrical vehicles o Distributed generation o Energy saving o Demand for energy reporting
4. Social environment (ethics, values etc)	o Energy saving will stay fashionable o Market ready distributed generation may increase the production in network a lot
5. Legal environment	o EU legislation o Expanding electricity markets/ electricity exchanges o Local regulation development for demands o Local regulation for cost savings o Recommendations and general laws concerning housing, energy and related issues o Dual point of contact and Supplier-centric market models for example for delivering energy savings related services (Including metering or some parts of it).

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6. Smart Grids and plug-in vehicles

Author: Antti Rautiainen

INTRODUCTION

Today's power industry is in the middle of remarkable changes. Climate change and other environmental issues, the opening of the electricity markets and pursuing more efficient operation of them, and ageing of network assets have set and will further set new requirements for power systems. Technological development, especially in ICT sector, brings new possibilities for power systems. In the future there will be more and better communication systems, more measurements, more computation capacity, better models and more controllable resources available than previously. To fulfill the new requirements set for power systems and to improve the operation of them cost-efficiently, the new technological possibilities mentioned above could be applied. Concepts where the new technology and approaches are used in power systems is often called as "smart grids" [Ham10]. The European Regulators Group for Electricity and Gas (ERGEG) defines smart grid as follows [ERG10]: "Smart Grid is an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety". This definition describes the some way ideal smart grid or the goal to which power system development should be targeted. The relevant point in smart grids is that the "smartness" is not in use of the new methods but in the consequences of the use of the new methods.

Transportation has a very important function in today's society. Globally, the energy production of transportation systems is highly dependent on oil, and there are strong expectations that the price as well as the volatility of the price of oil will increase in the future. The transportation sector is also a significant consumer of energy and a significant source of greenhouse gases and other emissions [Dav09]. Today's climate and energy policies imply strongly towards diversification of transportation fuels, improving energy efficiency and reducing emissions. The use of electrical energy in a broader manner by means of plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV) offers a potential to partly fulfill these challenging requirements. Emission reductions and the amount of primary energy conservation due to plug-in vehicles are, however, highly dependent on the energy system. Fig. 1 shows a numerical example, which is calculated with certain assumptions, about the influence of plug-in vehicles on CO2 emissions and primary energy consumption of Finnish passenger cars with different electricity production mixes. It is assumed, that 70 % of plug-in vehicles' kilometers are driven using electrical energy. It can be seen, that reductions in CO2 emissions and primary energy consumption are highly dependent on the energy source which is used de facto to produce the electricity charged by plug-in vehicles.

Plug-in vehicles are only a single way to contribute to reduction of oil dependency, reduction of primary energy consumption and reduction of CO2 emissions. It seems obvious that to achieve sustainable transportation system many other ways are also needed. Such ways are for example reduction of fuel consumption of conventional internal combustion engine (ICE) based cars, development of bio fuels, development of other alternative fuels and development of public transportation such as electrical rail traffic.

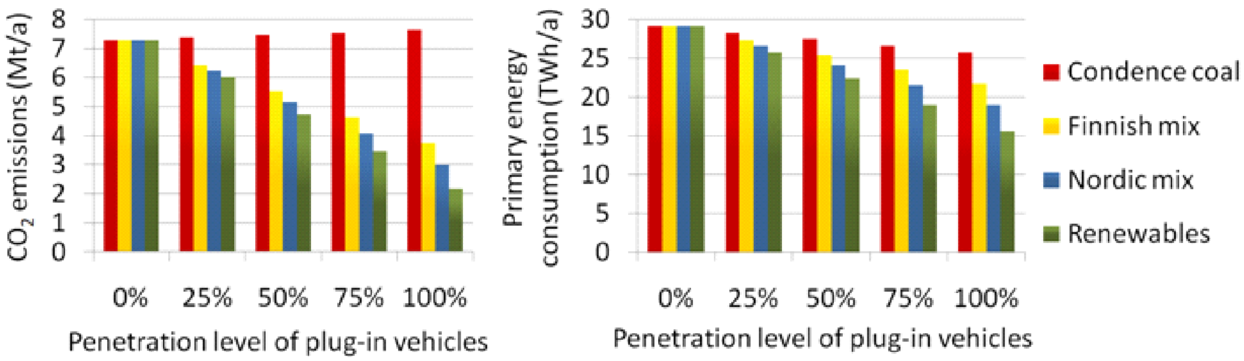

Fig. 1. The influence of plug-in vehicles on CO2 emissions and primary energy consumption of Finnish passenger cars

There are some barriers related to high penetration of plug-in vehicles (PHEV and EV). It is widely believed, that PHEVs and EVs will become common within some time frame, but there are differences of opinion about when and at what rate the market penetration will happen. The most important barrier is the battery technology. Batteries suitable for transportation appliances are very expensive at the moment, but the technology is continuously evolving [Scr10] and prices are expected to go down [Lac10]. PHEVs do not require necessarily very large batteries, as fairly high proportion of driving can be done using electrical energy even with fairly small battery packs. Fig. 1 illustrates cumulative shares of driving of Finnish people as a function of length of a trip. Data of fig. 1 is conducted using data from Finnish National travel survey 2004–2005. It can be seen, that about half of driven kilometers are driven as trips shorter than 50 km. Depending on the charging opportunities, PHEVs having electrical range under 100 km can reach very high proportion of kilometers driven using mainly electrical energy. Secondly, a lack of adequate charging infrastructure is a major barrier. A massive installation of charging infrastructure would probably be fairly expensive especially in urban areas.

SMART GRIDS AND PLUG-IN VEHICLES

Smart grid concept and plug-in vehicles can be linked to each other in many ways. Research related to plug-in vehicles is increased remarkably during the latest years. There are many important research questions, and some of them are discussed briefly in the following.

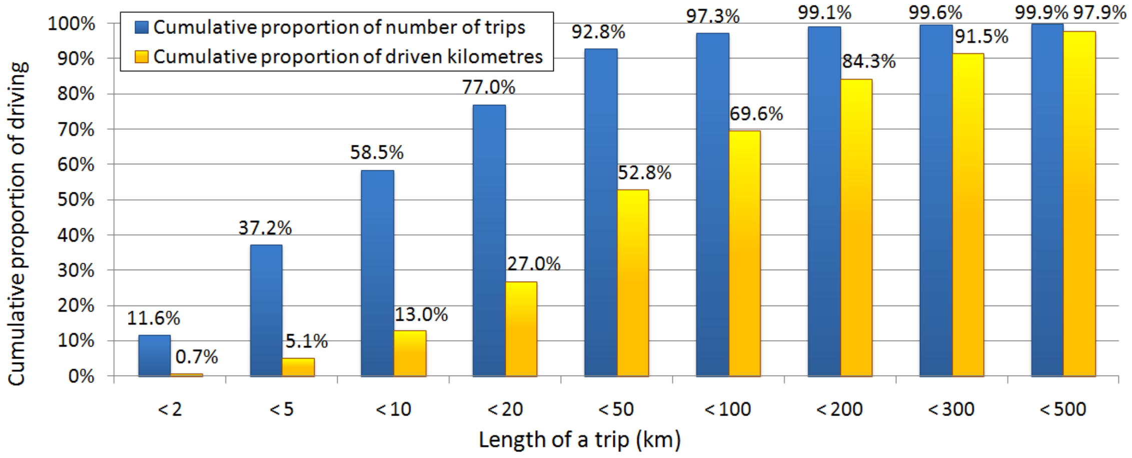

Fig. 2. Cumulative share of number of trips and driven kilometers as a function of a length of a trip

What are the impacts of plug-in vehicles to loads of the electricity networks and what does it mean for the networks?

Vehicle battery chargers affect the power system. Plug-in vehicles are not very big loads when considering the amount of energy absorbed. For example, there are about 2.5 million registered passenger vehicles in Finland today. According to latest National travel survey conducted in Finland an average yearly mileage of Finnish cars is about 18 000 km. If the average specific electricity energy consumption of the vehicles were 0.2 kWh/km and if all passenger vehicles were plug-in vehicles which use only electrical energy, the total yearly need for electrical energy of the vehicle fleet would be 9 TWh, which is roughly about 10 % of the total electricity consumption of Finland. This can be thought to be roughly the upper limit.

Plug-in vehicles can be, however, large loads when considering instantaneous power. To assess the impacts of plug-in vehicles on power system, the effect on the electrical load of a plug-in vehicle fleet in a power system has to be modeled. There are many issues which have an effect on the impacts of plug-in vehicles on the load levels of an electricity network. Such issues are for example car use habits, specific electricity consumption of vehicles, charging opportunities, battery capacities, available charging powers and electricity tariff applied by the vehicle users. As for example car use habits and typical driving distances different in different countries, national investigations are needed. To model plug-in vehicle load, it would be ideal if long lasting measurements of charging of large number of test vehicles could be carried out in large number of different types of charging spots. At this time, data of such a research is not available, and to perform such a research a large number of modern plug-in vehicles and extensive experimental arrangement including charging infrastructure and appropriate measurement would be needed. Thus, to assess today the effect of plug-in vehicles on the load of electricity networks, some other approaches have to be applied. The author of this text has exploited the results of National travel survey of Finland in developing a method for construction of statistical load models for plug-in hybrid electric vehicles especially in Finnish transportation system. This approach brings of course uncertainty in the results as many justified and heuristic assumptions have to be made.

It is known from some simple case studies, that a great penetration level of plug-in vehicles can increase dramatically the peak powers of different parts of an electricity distribution network [Las09]. Moreover, if high charging powers (for example in the case of three-phase chargers) are used, a plug-in vehicle can increase the peak power and increase the rating of the main fuses of a single residential network.

Could the charging system be designed to be smarter to mitigate possible harmful network impacts?

Using “smart” charging vehicle fleet could participate to the management of the electricity distribution network. The aim is to use lines and transformers nearer to their economic-physical limits. Smart charging operates to avoid the excessive overloading of network components. In the case of overloading time response requirements depend on the component under overload and weather conditions such as outdoor temperature. Depending on the system, the over-current protection of the network may or may not be set to trip because of overload. If overload situations are covered in the protection system, the electricity network management service should operate before the protection system. This type of service is based on state estimations of the network and may require a high level of coordination in order to operate extensively in different network states. This type of services can be however realized for different degrees of scale. One must not manage the whole distribution network, but a part of it such as a single problematic medium voltage feeder can be also the target of this service.

As mentioned earlier, distribution networks may experience dramatic load changes due to plug-in vehicle charging. Smart charging can be treated as an alternative for network reinforcements. These smart charging methods can be divided in two groups: services which need and services which do not need a communication system to realize control actions [Rau10]. The latter type can, however, include a communication system to receive setting values and parameters for their local operation. Services which do not need a communication system for control are simple when it comes to their operation and realization. Services based on communication systems make more sophisticated control operations possible. However, these services are more complex and require greater investments on the system. If the services are based on communication, DSO can monitors the state of the network using distribution management system (DMS) and advanced metering infrastructure (AMI) and send information to the vehicle chargers and other resources. Different services provided by vehicles acting as controllable loads are described in [Rau10].

Could the operation of the power system or electricity market be improved by smart charging?

The actors of power system and electricity market could use plug-in vehicles to improve the operation of power system or electricity market in many ways.

Energy companies could use plug-in vehicles for a resource, among other controllable resources, for demand response (DR) based on electricity price. This means that customers modify their energy consumption, for example charging of plug-in vehicles, in accordance with the electricity price [Alb08]. Customers benefit from DR actions in a form of electricity price reductions or some other type of fees [Alb08]. Balance management service, which is also a demand response service, is another service which energy companies might use. In Nordic electricity market energy companies are responsible for two different balances: production balance and consumption balance. Realized consumption and realized production form an important part of these balances. Using the aggregated resource an energy company could adjust the realized consumption and the realized production during operation hour to improve the balances. This is made to avoid possible additional costs of purchasing balancing services from the open deliverer/supplier or in the balance power market. The difference between balance management and other DR functions is that balance management tries to change the real consumption closer to a value bought from the electricity market, and some other DR functions are used to manipulate the energy which has to be bought from the market. There is also a separate balance power market in Nordic countries which is administrated by Nordic TSOs. Using aggregated resource one could also participate to that market.

Plug-in vehicles can be used to provide different reserve services for the TSO. A simple way to realize automatically activating disturbance reserve, which operates in grid disturbances, or frequency regulation service, which operates in normal grid conditions, is to make charging dependent on locally measured grid frequency [Rau09]. Control based on local measurements is an effective way to utilize large number of distributed resources which have to react to frequency disturbances in a very dynamic manner. Also, severe frequency disturbances occur fairly rarely, and the harm caused by a control method like this to the vehicle user can be very small as a whole, but the importance to the power system can be remarkable. Vehicles could also provide manually activated disturbance reserve which could be offered directly to the TSO. This service is very similar to the one offered on the balance power market, but disturbance reserve is used only during grid disturbances.

What are the impacts of plug-in vehicles to the functions of the electricity market?

Plug-in vehicles are mobile electric loads and can be charged in many physical locations. There are many possible market mechanisms, see [Rau10], which could be applied to give the vehicle users different levels of freedom to choose the electricity product when charging in public charging spots. Users could choose for example the cheapest or a renewable energy based electrical energy product.

Could the electrical energy storage of plug-in vehicles used for the needs of the electricity network and market?

In the context of power systems, plug-in vehicles can be used as controllable loads or as dischargeable energy storages. Efficient and cost effective energy storage capacity would offer many advantages and possibilities which are analyzed for example by [Jew04]. Storages could be discharged to public distribution networks (Vehicle-to-grid – V2G) or to small isolated network islands such as single households (Vehicle-to-home – V2H). V2G and V2H functionalities are very interesting because of their ability to store fairly big amount of electrical energy for the needs of the future. If 50 % of cars in Finland were plug-in vehicles with an average effective energy capacity, which can be thought as the depth of discharge measured in kWh, of 20 kWh, the total energy storage formed by these vehicles would be about 25 GWh, which is a fairly big amount of energy in the Finnish power system. Also, the cost of this storage can be thought to be fairly low because these vehicles are purchased primarily for driving purposes, and a possible electricity storage use is only an ancillary service.

Although discharging offers many interesting possibilities, it includes also some challenges. Charging-discharging cycles caused by discharging operation pose additional stress to batteries and decrease their cyclic lifetime causing additional costs for vehicle owners. However, as the cyclic lifetime of batteries increases and prices go down, this issue becomes less important. Also the vehicle users have to accept that the state-of-charge of the batteries of their vehicles can decrease during connection to the electricity network. However, these challenges can be tackled by relevant customer incentives. If a concept taking the user point-of-view well into account and including sufficient economical incentives is developed, energy storage application of plug-in vehicles could be realized.

V2G function could be used for similar purposes as controllable load presented previously with smart charging, but in addition to stopping or restriction of ongoing charging, V2G offers possibility to discharge energy storage at any time when connected to grid.

An individual vehicle can also be used to provide some local services, such as backup power, at the charging site. During an electricity distribution outage the batteries of the vehicles could be used as energy storages to feed a small network island in a network, such as a single household. Vehicle chargers could also be used to improve power quality in a local distribution network. This means for example mitigating voltage dips, harmonics and asymmetry.

What kind of a network interface is needed in plug-in vehicles?

Different “smart” functions of plug-in vehicles set different requirements for their network (includes also relevant information systems) interface. An interface between an energy management system and a vehicle can be divided in two parts: an electrical interface and an ICT interface. The electrical interface links the vehicle to the physical power system. The ICT interface links the vehicle to the information systems which is needed to realize different services.

The requirements for the interfaces depend on the functions which the vehicles should be able to carry out [Rau11].

What kind of user incentives and market mechanisms are needed to realize different “smart” services?

Different smart services offer different financial benefits and incentives for different parties. It is very important that vehicle users have a reasonable economic incentive to participate to different service markets with their vehicles and other energy resources. Creating services with such incentives is not necessarily easy in practice. Concepts of dynamic pricing, including dual tariff policy, of electrical energy and electricity transfer are presented often as incentives. The energy needs of a vehicle are not, however, very large. When considering today’s electricity price volatility in Nordic markets the benefits provided by dynamic pricing of energy to the customers may be too small. Markets are changing and the Nordic system is integrating with the other European systems, and this will probably reduce the volatility of the prices. However, plug-in vehicles are only a single type of resource, and using some other loads sufficient volume could be obtained.

Different kinds of dynamic transfer tariffs could also be developed. One option is to apply power based transfer tariff covering all electricity consumption of domestic consumers. Technically this could be realized by intelligent energy meters. Another way to realize a dynamic transfer tariff is to change the tariff via communication in accordance of the free capacity of the network

For different parties it is necessary to allow the aggregation of small resources and treat the aggregated resources as a single, larger, unit. Thus, an aggregator is needed in the system, which aggregates all the small resources. Also, the aggregator must have reasonable revenue possibilities for its operation. Different actors cooperating with the aggregator, such as energy companies and network companies, must also have reasonable economical incentives to apply the services. For energy companies such incentives could be formed by means of more efficient electricity trade and for a distribution network company such incentive could be peak load reduction and avoidance of some network reinforcements.

CONCLUSIONS

In this report, plug-in vehicles were considered as a part of a smart grid concept. If plug-in vehicles get very common in the future, they offer many interesting opportunities for different parties of power system and electricity market. In the beginning of the market penetration of plug-in vehicles only the mandatory functionalities will probably be applied, but when the penetration level increases, other functionalities and services might become economically attractive. Because plug-in vehicles are not widely commercialized yet and the charging infrastructure is also under development, there is a possibility to develop a sophisticated system. Although plug-in vehicles are mostly discussed in this text, it is very important to remember that these vehicles are only one type of a resource which could be used in a “smart grid” context.

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7. Active voltage control in distribution networks including distributed generation

Author: Anna Kulmala

INTRODUCTION

The amount of distributed generation (DG) is constantly increasing. The European Union has set ambitious targets of 20 % share of energy from renewable sources by 2020 [1] to reduce gaseous emissions, diversify the energy supply and reduce dependency on fossil fuel markets. To meet the overall renewable energy target a substantial increase in the share of renewable energy sources in electricity production is needed. Renewable electricity is often produced in relatively small power plants whose location is determined by external factors such as wind and solar resources. Hence, power plants using renewable energy sources are often connected to distribution networks. Also, deregulation of energy markets has made distribution network access available to all energy producers and the prices of small generating plants have reduced. [2]

The structure and control methods of existing distribution networks are designed based on the assumption of unidirectional power flows. When the penetration level of DG increases, this assumption is no longer valid and the operation and planning principles of distribution networks need to be revised. DG can influence the distribution network in many positive ways, e.g. voltage support or loss reduction, but also some problems may arise. These include for instance voltage rise problems, protection problems and increase in network fault levels. [2]

In weak distribution networks the capacity of connected generators is usually limited by the voltage rise effect. Also the transient voltage variation at generator connection or disconnection can in some cases turn out to be the limiting factor. At present, DG is usually considered merely as negative load in distribution system design and the amount of DG is limited based on extreme conditions of minimum load/maximum generation and maximum load/minimum generation. It is assumed that DG can not participate in the control of distribution networks in any way. [2]

At present, voltage rise is usually mitigated by reinforcing the network (increasing the conductor size or connecting to a dedicated feeder) and the operational principle of the network is not changed. This can, however, be quite expensive. Also active voltage control methods can be used to reduce the maximum voltage in the network. Active voltage level management can in many cases increase the allowed penetration of DG substantially and, therefore, lower the connection costs. [3]

Several active voltage control methods of different complexity and data transfer needs have been proposed in publications. The simplest active voltage level management methods are based only on local measurements and do not require additional data transfer between distribution network nodes. On the other hand, the voltage of distribution networks can be controlled using an advanced distribution network management system which controls all components capable of voltage control (e.g. tap changers at substations, voltage regulators, power plants, compensators and loads) and requires a lot of data transfer between network nodes [4]. The most suitable control method is selected based on the structure of the network and the number of components participating in the control [5]. This report presents a survey of different active voltage control methods.

ACTIVE VOLTAGE CONTROL METHODS BASED ON LOCAL MEASUREMENTS

The simplest active voltage level management methods are based only on local measurements but can still, in many cases, increase the capacity of connected generation to existing networks substantially [3]. The reactive and active power of DG can be controlled based on the terminal voltage. Also loads and compensators could be controlled based on local measurements.

Local reactive power control

Voltage rise caused by DG can be decreased by allowing the generator to absorb reactive power. At present, DG is usually operated with unity power factor and is not allowed to participate in distribution network voltage control. However, if DG controlled its reactive power based on its terminal voltage (in other words operated in voltage control mode) the distribution network voltage level would vary less between different loading conditions and more DG could be allowed to connect to the network as the voltage rise would be decreased. If power factor control is preferred, the controller could operate in power factor control mode when the terminal voltage is within determined limits and switch to voltage control mode when the limits are overstepped [6]. [7], [8]

The reactive power control capability of DG depends on its network interface. Power plants with synchronous generator or power electronic interface are capable of controlling their active and reactive power independently as long as their operational limits are not exceeded. When induction generators are used the reactive power is dependent on the active power and can not be controlled unless some kind of controllable reactive power compensation device is used. At simplest the consumption of reactive power can be increased by disconnecting the power factor correction capacitors usually fitted at the generator terminals. If a power electronic compensator (STATCOM, SVC) is connected to the generator terminals the reactive power can be controlled continuously. [2]

If local reactive power control is used its effect on network losses has to be considered. The additional reactive power flow can also increase the need of reactive power compensation capacitors at the substation and increase the number of main transformer tap changer operations. However, if excessive voltage rise is expected to happen only occasionally the network's total costs can diminish significantly if large investments (network reinforcements) can be avoided. [9]

Production curtailment

Voltage rise can be decreased also by reducing the active power output of DG. If the voltage limit is exceeded only rarely the DG owner might find it beneficial to curtail some of its generation at times of high voltage if allowed to connect a larger generator to the network. The simplest method to implement production curtailment is to disconnect a required number of generating units when the voltage exceeds its limit. If the active power of DG can be controlled for instance by blade angle control of wind generators, disconnection is not required as the active power control of DG can be continuous. [3], [9]

COORDINATED VOLTAGE CONTROL METHODS

Coordinated voltage control (CVC) methods utilize information about the whole distribution network. The methods can determine their control actions based on control rules or use some kind of optimization algorithm.

Usually, coordinated voltage control methods change the set points of lower level controllers (for instance [10], [11]) but also implementations that alter the lower level controllers or control the actuating devices directly have been proposed [12], [13]. The first approach is likely to be the one that will be used in real network implementations because the lower level controllers do not need to be changed but only the upper level controller and communication infrastructure need to be added.

Methods Based on Control Rules

CVC methods based on control rules are suitable for simple networks where only few control possibilities exist [5]. Traditional radial distribution networks are such networks.

The simplest and most studied CVC method controls substation voltage based on network maximum and minimum voltages [10], [14], [15]. The substation voltage is controlled by changing the set point of substation automatic voltage control (AVC) relay that in turn gives commands to the on load tap changer (OLTC) of the main transformer. The control principle is simple: Substation voltage is lowered if network maximum voltage exceeds its limit and increased if network minimum voltage falls below its limit. If both voltages exceed feeder voltage limits, nothing is done because the voltages can not be normalized by controlling substation voltage. In [15] the algorithm is further developed to prevent hunting of the tap changer and to restore the voltages to a normal level after for instance disconnection of DG.

The reactive power of DG can be controlled based on local measurements [7] in which case the reactive power control of DG will always operate faster than possible coordinated control of substation voltage. Control of DG reactive power can also be included in the CVC algorithm which would determine both the substation voltage and reactive power of DG [16] although determination of control rules becomes more difficult when the number of controllable components increases.

In [17] and [18] a continuous control algorithm that aims to keep network voltages near their nominal value is proposed. The control algorithm can also be such that control actions are taken only when either network minimum or maximum voltage is approaching its limit. In [19] main transformer OLTC position, voltage regulation mode of the substation AVC relay and the generators’ reactive power output are controlled to keep the voltages between acceptable limits. In [20] main transformer OLTC is the primary control variable and DG reactive power is controlled only if the voltages can not be restored between acceptable limits by substation voltage control. A ranking table is used in generator reactive power control. In [11] a modular algorithm that controls substation AVC relay set point and DG AVR set point is proposed. The algorithm aims to keep network voltages between acceptable limits and includes also a part that restores the controlled variables to their original state when control is no longer needed.

The benefit of using control rules is the simplicity of the method. Time domain implementation is straightforward and no convergence problems occur. However, when the number of controllable components increases determination of control rules can become a complex task. In these cases, methods using optimization algorithms can be more suitable.

Methods Using Optimization

Several CVC methods using different optimization methods and objective functions have been proposed in publications. In [3] and [5] optimal power flow (OPF) is used to determine the most profitable state of control variables. In [3] the OPF objective function is formulated to minimize the active power curtailment whereas in [5] the costs of transformer tap operation, reactive power absorption and active power curtailment are minimized. Both algorithms control the substation voltage and reactive and active power of DG. OPF is used also in [13] where the tap positions of substation main transformer and step voltage regulators on feeders are controlled.

In [21]-[24] genetic algorithm is used to determine control actions. In [21] the algorithm controls the main transformer OLTC, step voltage regulators (SVR), static VAr compensators (SVC) and shunt capacitors and reactors. The objective function is formulated to keep the network voltages near their nominal value and to reduce losses. In [22] and [23] the genetic algorithm is used to minimize the difference of network voltages to nominal. In addition to main transformer OLTC and DG's reactive power shunt capacitors are controlled in [22] and step voltage regulators in [23]. In [24] the objective function is formulated to minimize network losses. The execution time of genetic algorithms is typically quite long which should be taken into account if the algorithm is intended for on-line control and not only off-line studies.

In [25] a local-learning algorithm in conjunction with multiobjective optimization and a supervisory process is used to determine the set points to voltage controlling devices. The objective function takes into account active power losses, average voltage deviation, maximum voltage deviation and reactive energy costs.

In [26] evolutionary particle swarm optimization is used to control the reactive power of DGs, active and reactive power of microgrids and main transformer OLTC. The operation of microgrids is emulated by an artificial neural network to reduce the computational time needed. The objective function aims at reducing active power losses and keeping network voltages between acceptable limits.

Reference [27] proposes a CVC method that uses state machine approach to control substation OLTC and reactive and active powers of DGs. The new set points for DG powers are computed based on a predetermined contribution matrix and optimization. In [28] a multi-agent system is used to realize control of substation OLTC and active and reactive powers of DGs.

Some practical issues need to be taken into account when CVC methods based on optimization are used. The computational time required for the optimization can not be too long if the method is intended for on-line use. The algorithm should also know how to operate if the optimization algorithm does not converge. Also, the algorithm should know the order in which control actions need to be executed if multiple control actions are suggested. Moreover, the control solution obtained from the algorithm should not radically deviate the network from the current operating point. [5]

Real Implementations

Although several CVC methods have been proposed in publications only few real implementations yet exist. This is due to at least the following reasons: Firstly, measurements on distribution networks are currently in many cases restricted to substation and precise information about the state of the network is not available. However, the amount of measurements in distribution networks is constantly increasing as automatic meter reading (AMR) devices are being installed. The AMR measurements can be used to improve the accuracy of distribution network state estimate [29] which makes CVC more attractive.

Secondly, most publications on CVC (especially those using optimization) concentrate on determining the control principles of the control algorithm and do not address the time domain implementation of the algorithm and practical issues in taking the algorithm in real distribution network use. Hence, demonstrations are still needed to make CVC feasible for distribution network operators.

References [30]-[32] describe the operation and commissioning of a commercial product GenAVC that implements coordinated control of substation voltage through control of ACV relay set point. The device includes a state estimator and a CVC algorithm based on [10]. It has been successfully in operation in three different network locations [33].

The operation of the CVC algorithm proposed in [11] has been demonstrated in Real Time Digital Simulator (RTDS) environment [34] and also in a real Finnish distribution network.

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8. Connection of distributed generation units and loss-of-mains protection

Author: Ontrei Raipala

INTRODUCTION

The energy sector is currently facing serious challenges such as depletion of fossil fuels and the need to reduce gaseous emissions. These challenges have led to a growing interest towards renewable energy sources. Generating units based on renewable energy sources are often relatively small sized which makes it uneconomical to connect these units to high voltage grid. This is also true for small scale generation units based on conventional energy sources which are also regaining interest because of reasons such as modular structure, short lead times and smaller required capital. A steadily increasing amount of small distributed generation (DG) units is thus now being connected to distribution networks which have traditionally contained very little generation.

The planning and operation of distribution networks have been fairly simple because of the unidirectional flow of power. This stems from the fact that all the generation units have traditionally been connected to transmission networks, whereas, the purpose of distribution networks has solely been to deliver the power flowing from the transmission networks to customers at low voltage network level. The small scale distributed generation (DG) units are now changing the role of distribution networks and invalidating the assumption of unidirectional power flow. This raises new challenges like problems with protection, changing voltage profiles and rising fault levels. [Jen00] The common solution to these problems is to reinforce the primary network infrastructure so that it is able to cope with all possible extreme conditions. This kind of way of dimensioning distribution networks leads to a fairly low utilization rate of the network since the dimensioning extreme conditions can be very rare [Rep05]. The high costs related to this traditional way of managing distribution networks have raised a question whether there would be a more reasonable network management concept.

The smart grid concept is a new kind of approach for dealing with the challenges raised by DG. There is no universally agreed definition for this concept at the moment but some attributes regarding this concept appear to be common. The basic idea in this concept is to respond to the future challenges raised by the growth of DG, increased demands on power quality and to maximize the use of network assets. Both the EU and the USA have showed great interest for this intelligent network concept and created their own visions of future networks [Eur06, MGI07]. The visions of these two players seem to emphasize similar kinds of characteristics like flexibility (coping with customer needs, growth of DG and other future challenges), accessibility to all parties (e.g., integrating all DG to network), reliability (meeting increased requirements regarding supply reliability), economic efficiency (maximal utilization of assets) and resiliency (resilient to natural disasters and rapid supply restoration times).

Network protection and automation play a vital role in achieving many of the goals set in the smart grid visions (rapid restoration times, increased supply reliability, integrating all DG). One of the major protection challenges with DG is related to anti-islanding protection (also known as loss of mains (LOM) protection. All DG installations need to be equipped with appropriate LOM protection which ensures that no DG units are unintentionally left feeding an isolated network section alone without the support of the main grid. The main reasons for the non-acceptance of unintended islanding are:

- An isolated DG unit can cause safety hazards to utility personnel by back feeding isolated lines that should be de-energized for maintenance purposes
- Customer devices fed by an isolated DG unit can be damaged due to poor power quality in the islanded network section
- DG can cause automatic reclosing failures by maintaining the voltages on a line that should be de-energized
- DG as well as other network components can be damaged as a result of out-of-phase reclosing

Intentional islanding can, however, improve the reliability of power supply considerably in the future. This aspect should be also taken into account when designing LOM protection. In other words, LOM protection has to either be capable of determining when islanding is desired or a block signal of some kind will have to be sent the LOM IEDs that are not supposed to be tripped. There is currently lot of research ongoing concerning the development of a LOM protection scheme that has a high sensitivity and additionally good resilience against disturbances caused by remote faults. In addition to these features, the developed LOM protection schemes have to be affordable also for smaller DG installations. This report intends to survey and discuss the above mentioned requirements set for the functioning of LOM protection for smart grids.

LOSS OF MAINS PROTECTION AND THE NON-DETECTION ZONE

Most of the LOM protection methods are based on detecting the changes in some system quantities like in voltage and in frequency, which usually take place when a network section is islanded. These changes are mainly caused by the imbalance between real- and reactive power production and consumption in the islanded network. There is, nevertheless, a risk that this imbalance is so small that transition to island mode does not cause any of the quantities measured by a LOM relay to drift out of the preset limits. In cases like, the LOM protection fails to detect islanding. This blind area of LOM protection in the surroundings of the production- consumption equilibrium is called the non-detection zone (NDZ). [Mäk07] Figure 1 shows what the NDZ for traditional overvoltage- (OVP) / undervoltage protection (UVP) and overfrequency- (OFP) / underfrequency protection (UFP) might look like.

The U > Umax marking in the figure refers to the OVP limit, whereas, the U < Umin marking refers to the UVP limit. Respectively, the markings f > fmax and f < fmin refer to the OFP and UFP limits. This kind of traditional voltage and frequency protection is probably the most utilized LOM detection method due to its simplicity.

The imbalance between the production of a DG unit and the consumption of local loads varies throughout the day. This imbalance is usually balanced by the import/export from/to the main grid. Because of this variation, the risk of unintended islanding also varies throughout the day as figure 2 illustrates.

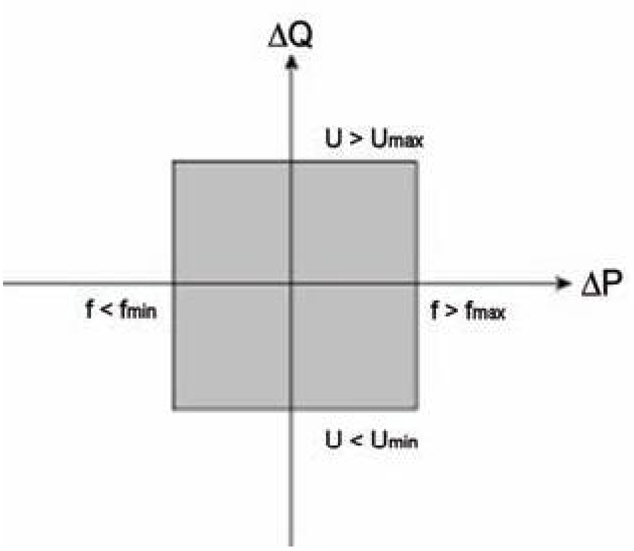

Figure 1. Non-detection zone for traditional voltage and frequency protection [Mäk07]

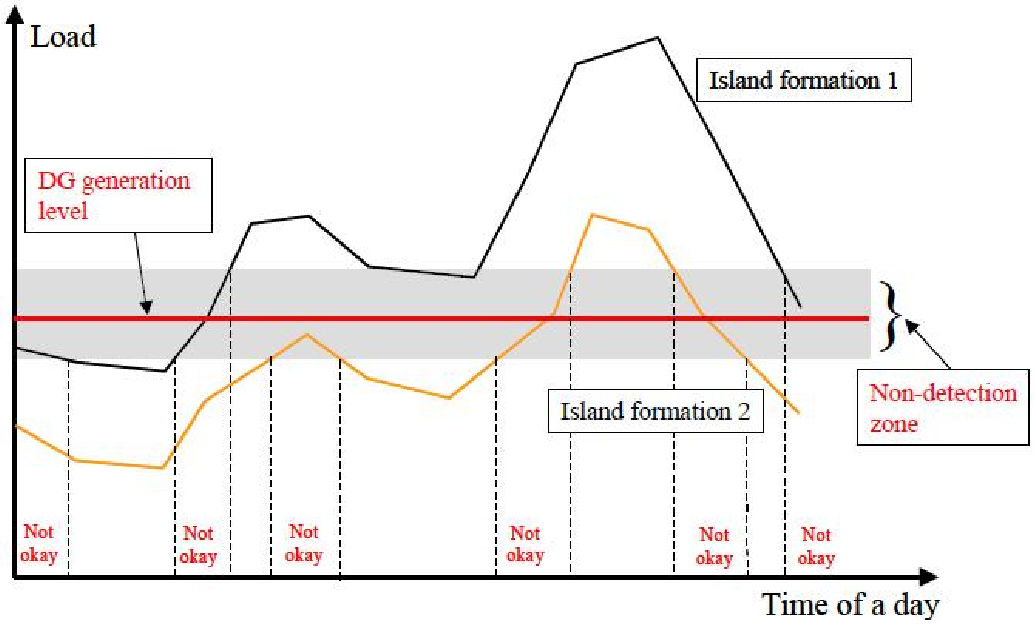

Figure 2. The impact of varying demand on LOM protection [Xu04]

There is, however, also another factor that affects the risk of non-detected islanding. This is the fact that a DG unit can become isolated from the main grid with various amounts of local loads, i.e., there are usually many network nodes from which a tail part of a feeder can become isolated from the main grid. The black and yellow curves in figure 2, which represent the demands of two different sets of local loads, illustrate this issue. The areas that are marked with the text “Not okay” in the figure represent the periods during which LOM protection would fail to detect islanding. [Xu04]

It is noteworthy that delays in the operation of LOM protection may occur even with larger power imbalances. Such delays can also be very harmful because of the high requirements regarding the operation times of LOM protection that are set by fast autoreclosing. This stems from the fact that all DG units should be disconnected within the open time of autoreclosing from the feeder in question. This can be quite challenging if very short autoreclosing open times (usually from 0.2s to 2s) are used. [Ple03] It should also be born in mind that it is not reasonable to increase the autoreclosing open times excessively because it has a degrading effect on power quality. The size of the NDZ as well as the operation times of LOM protection can, of course, be reduced by using stricter LOM protection settings. This, however, brings another problem which will be discussed in the next chapter.

CONNECTION REQUIREMENTS

DG units have typically been considered to have merely a marginal effect on the power system and system operators have, therefore, allowed them to disconnect immediately after any disturbances. Sensitive LOM protection settings are preferable for DNOs because they prevent DG units from maintaining fault arcs thus enabling simple and safe removal of temporary faults by auto-reclosing. Out of phase reclosings can cause dangerous stresses to DG units, which makes fast disconnection of DG units preferable also for the unit owners. The amount of DG has, however, already reached significant levels in some regions and consequently the responsible TSOs in these areas have realized that too sensitive protection settings of DG units can have detrimental effects on the system stability. [Ple03, Tut08] This stems from the fact that faults in the transmission network can launch huge amounts of adverse tripping of DG which was, for instance, witnessed during the UCTE disturbance in the 4th of November 2006 [UCT07].

Many system operators have recently issued grid codes for DG that define how long the generating units have to be able to stay connected and support the system stability during various kinds of disturbances. These are also known as the fault ride through (FRT) requirements. Figure 3 represents fault ride through requirements for wind turbines in the networks of various TSOs.

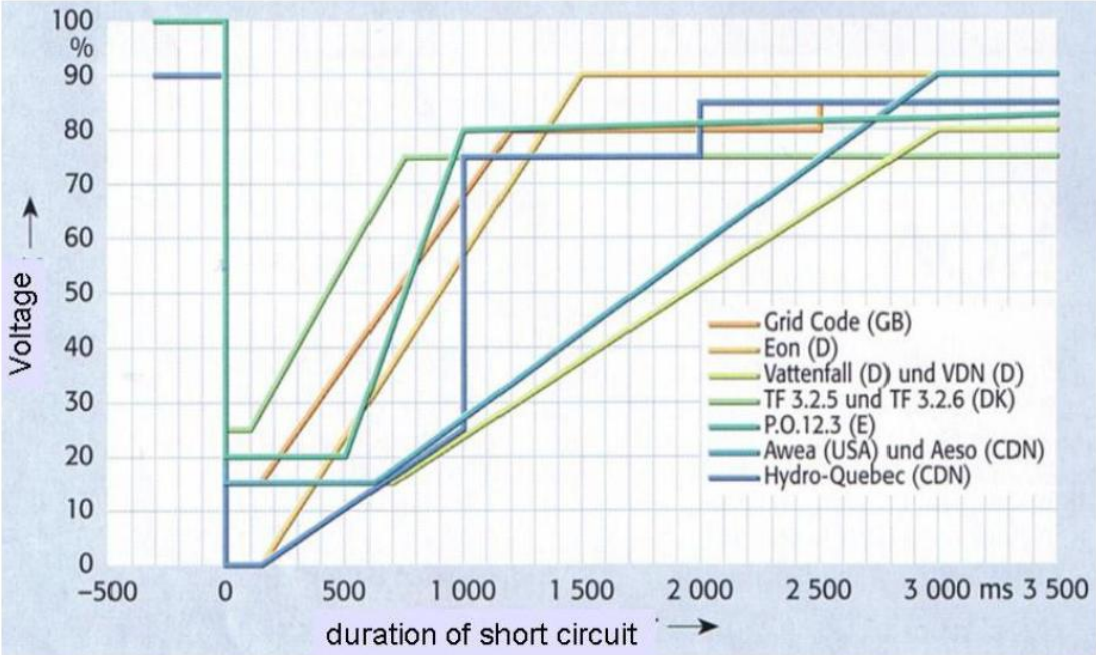

Figure 3. Fault ride through requirements of various TSOs for wind turbines [Tut08]

The vertical axis shows the voltage dip experienced by the wind turbine, whereas, the horizontal axis represents the voltage dip duration. FRT requirements are mainly meant for HV connected wind farms, but it is likely that similar kinds of requirements will be issued for MV connected units in the future as well especially in areas of high DG penetration level. DG units should also withstand greater variations in the system frequency. This would benefit the system stability and facilitate the utilization of intended islanding for improving the quality of supply. [Tut08]

FRT capability means that a generation unit is capable of enduring deep voltage dips and feeding reactive power to the system thus supporting the network voltage. It is, however, not enough that the generation unit has FRT capability, but also the LOM protection relay of the unit must be set to enable the FRT operation. This means that the sensitivity of the LOM protection must be loosen which, in some cases, may pose a safety risk. [Tut08] The realization of the FRT capability thus increases the risk of unintended islanding not only because of the necessity of loosening the LOM protection settings but also because a DG unit that has FRT capability is more capable of maintaining power islands. In this sense, LOM protection settings are a compromise of some kind between enabling FRT and avoiding unintended islanding. Figure 4 illustrates how fulfilling the FRT requirements extends the size of the NDZ.

As discussed, LOM protection has to be set to allow FRT. It may, however, be quite troublesome to try configuring the LOM relays to function according to the country or TSO specific FRT curves with existing relays as discussed in [Lei09]. An example of this laborious task can be seen from figure 5 which shows the rough form of Portuguese FRT requirement curve which the authors of [Lei09] have configured in a commercial LOM relay.

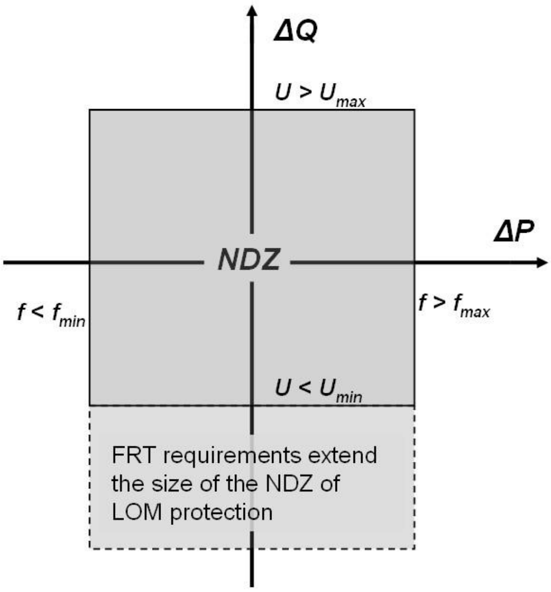

Figure 4. Loose UVP settings increase the size of the Non-detection zone

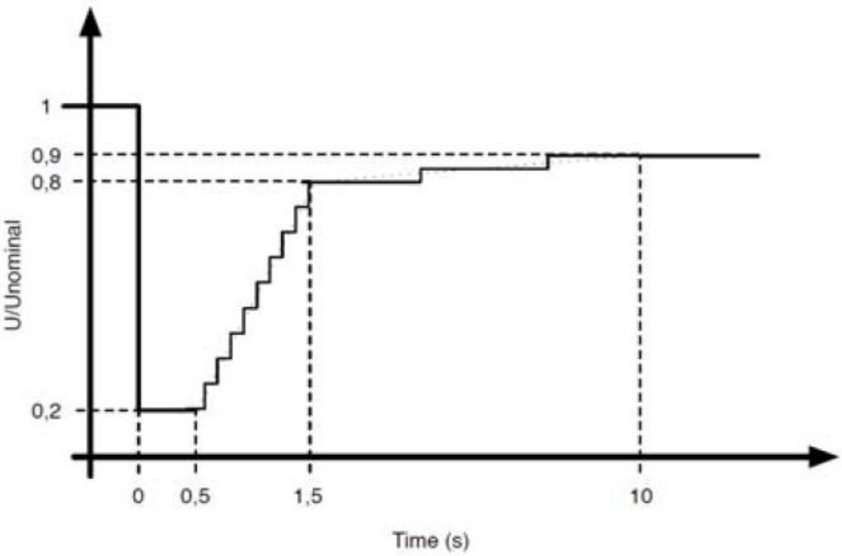

Figure 5. The Portugese FRT requirement curve set in a commercial LOM relay

The curve in figure 5 had to be only an approximation of the real Portuguese FRT requirement curve because of the lack of logical configurable gates in the relay that the authors of [Lei09] utilized. Relay manufacturers should, therefore, definitely take the FRT requirements better into account and develop UVP functions in which the FRT curves are easily configurable.

CATEGORIZATION OF THE LOM DETECTION METHODS

LOM detection methods can be divided into three categories. These are communication based methods, local passive methods and local active methods. Figure 6, which is based on [Sam07] and [Mah08], illustrates this division into the three categories and gives some examples of each category. Reference [Mah08], however, suggests that there is actually a third subgroup in local methods which and names it as hybrid techniques.

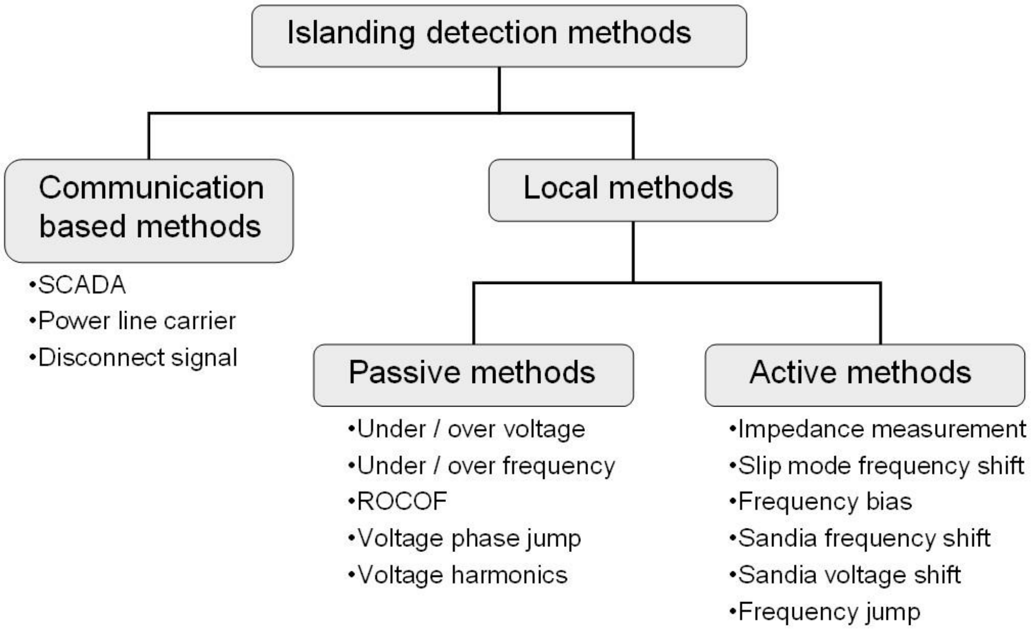

Figure 6. The categorization of LOM detection methods, reproduced from [Sam07] and [Mah08]

Passive methods are based on locally measuring some system quantities like voltage and frequency. The idea in passive methods is that some changes in the measured quantities usually take place during the transition to islanding mode. Passive LOM detection methods are the most utilized ones due to their low cost and because they are applicable to all DG units. The transition to island mode can, however, sometimes be so smooth that passive LOM detection methods fail to detect islanding as already discussed. All passive LOM detection methods have a NDZ of some kind. The size of the NDZ can, of course, be reduced by applying stricter LOM protection settings but this, on the other hand, tends to cause unwanted tripping of DG units. Two of the most utilized passive LOM detection methods are ROCOF (Rate of Change of Frequency) and vector shift [Kum07].

Active LOM protection schemes are based on forcing the protected DG unit to try to make small changes in some of the system quantities like current waveforms and then detecting the response of the system. The idea behind this is that the DG unit is only capable of manipulating the system quantities when the connection to the main grid has been lost. [Sam07] Active LOM protection schemes are typically applied in inverter connected DG units because the inverter works as a suitable tool for implementing these small changes. [Mäk07] Active LOM protection schemes do not suffer from the NDZ problem but they usually provide slower detection because changing the system quantities takes time. [Aba07] Active methods are, however, not allowed in all networks because they have a degrading effect on power quality [Con09]. More information concerning these methods can be found from [IEA02] and [Brü06]

In the hybrid detection methods the idea is to combine the advantages of passive and active methods. In hybrid detection methods, a passive and an active method are combined in such a way that the active method is only used when the passive method suspects that the DG unit in question has become islanded. This brings the advantage that perturbations to the network are only inflicted when the passive detection method in question has first suspected islanding. Hybrid methods have small NDZ but they, on the other hand, provide slow detection times since two detection methods are used in sequence. [Mah08]

Communication based methods are not based on detecting any changes in system quantities and they are, therefore, immune to the NDZ problem. In these methods, whenever a circuit breaker is opened, the idea is to somehow signal all the DG units downstream that the connection to the main grid has been lost. Reference [Sam07] divides communication based methods in three categories which are the disconnect signal-, power line carrier- and the SCADA based method. In the disconnect signal scheme the idea is to such that a disconnect signal is sent to all relays downstream from the opened circuit breaker. The technique represented by [Rin09], which is based on inter IED communication, is an interesting variation of this method. This method also includes a blocking feature for the avoidance of nuisance tripping which is meant for cases where additional passive LOM protection functions are used in LOM relays for back up protection purposes. In the power line carrier method, the idea is to continuously send a subharmonic signal to the network from a central location with the help of power line carrier. Whenever a circuit breaker is opened, all the DG units downstream from this breaker stop receiving the signal and they can thus be tripped off the network. References [Kum07] and [Sam07] suggest that this method could be the best choice because it provides very reliable LOM protection with reasonable implementation costs. The idea in the SCADA method is to extend SCADA to cater all the DG units, which naturally requires extensive communication infrastructure. It is, however, questionable whether the SCADA method can provide operation times fast enough.

The conflict between having fast and sensitive LOM protection and, at the same time having FRT capability, can also be overcome by using communication based LOM protection schemes. One should, however, pay attention to the often utilized back up LOM protection functions because they need to be set to allow the FRT. Communication based methods in general seem to be superior to the other LOM detection methods from the technical point of view but they, on the other hand, require higher investments.

LOM PROTECTION AND INTENTIONAL ISLANDING

Both the USA and the EU have emphasized reliability of supply in their smart grid visions ([Eur06] and [Mgi07]). One key issue regarding reliability is the utilization of intended islanding. The transition from grid connected mode to island mode can be made to happen with or without an interruption. It is, however, considerably easier to do it with interruption.

The sequence leading to islanding usually begins by the operation of protection system after a fault. In such a case, the simplest way to change from grid connected mode to island mode is done by first disconnecting all the DG units in the power island area. The disconnection of the DG units is carried out by the LOM protection. Then, after separating the power island area by an appropriate switching operation, a desired amount of DG units in the power island area can be reconnected and black started (a certain amount of the generation in the power island needs to be capable of black starting) to feed the loads in the power island. The LOM protection schemes of the DG units in the power island probably need to be readjusted to allow the islanding. This readjustment of the LOM protection settings would not need to happen instantly/automatically in this case since an interruption was required anyway. The required readjustments would probably mean loosening of the limits in case of OFP/UFP & OVP/UVP functions and disabling in the case of more advanced passive and active LOM protection functions.

The transition to island mode can also be made to happen directly without an interruption. This requires a more sophisticated LOM protection arrangement that can immediately determine when the transition to power island is desired and when it is not. Figure 7 illustrates this problem. This practically means that it is necessary to use a communication based LOM protection scheme of some kind so that all the desired LOM IEDs could be signalled not to trip. The SCADA- (provided that sufficient speed could be achieved) and at least the disconnect signal LOM protection scheme presented by [Rin09] would be suitable for solving a situation like this. A power line carrier (PLC) method, where there was a signal generator only at the substation (common for this scheme), would not suit for this purpose. With certain modifications (see [Con09]) the utilization of the PLC scheme would, however, also be possible.

The IED controlling the circuit breaker separating the power island from the main grid would have to be equipped with synchronism check function in order to make it possible to reconnect the power island network back to the main grid without an interruption after the fault clearance. This IED would also have to be able to send control commands to the control systems of the DG units in the power island in order to carry out the possibly needed resynchronization.

DISCUSSION

Communication based LOM protection schemes seem to be superior in protection sensitivity (no NDZ), operation times (important for the use of fast AR) and in the ability of enabling the FRT of DG units. In addition, it is probably necessary to use communication based LOM protection schemes if some parts of the networks (e.g. microgrids) should be able to change to island mode without interruption. It thus seems obvious that communication based LOM protection schemes are better from the technical point of view. The only question with such schemes is the cost. Small DG installations cannot afford very expensive LOM protection schemes. Active and passive LOM protection schemes may still be the most reasonable choice for such customers.

All in all, well functioning LOM protection solutions already exist but they are costly. There is thus a clear market potential for a LOM protection scheme that has a reasonable price but still the ability to answer to the needs of smart grids (high sensitivity, rapid operation times and the ability to enable FRT as well as intentional islanding).

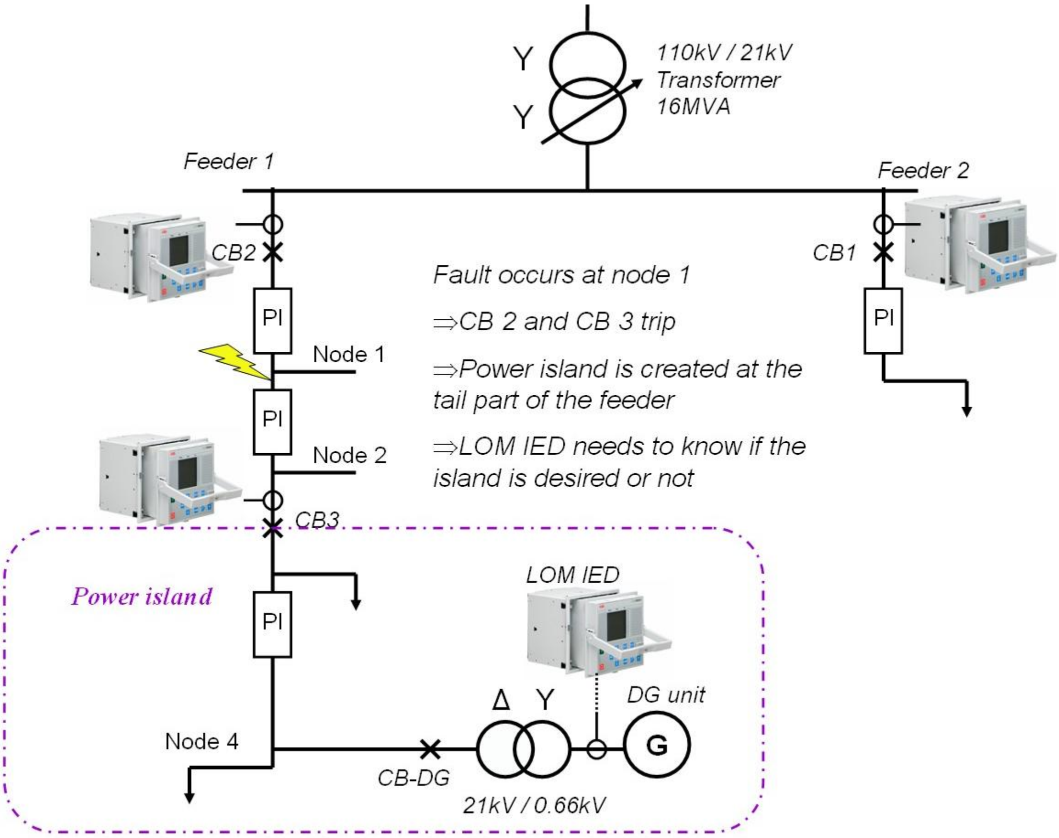

Figure 7. A challenge related to LOM protection

CONCLUSIONS

Integration of DG is often mentioned as one of the key drivers of smart grids. This is because there will be large obstacles related to the integration of DG if distribution networks are planned and operated according to the currently used (passive) strategy. Voltage rise issues, increasing fault levels and protection problems are often mentioned as the biggest challenges related to the integration of DG. Active (intelligent) network management concepts can be used to overcome these challenges without the need of making excessive investments in primary network infrastructure. One challenge related the integration of DG, however, still remains without a well accepted solution, namely the loss of mains (LOM) protection of DG (also known as anti-islanding protection). LOM protection should always disconnected the DG unit under its protection whenever this unit becomes unintentionally separated from the main grid, i.e., becomes islanded.

Unintentional islanding is not tolerated due to the severe impacts it can cause. These include safety hazards for both utility personnel as well as for network components. It is, therefore, important to detect and shut down unintentional islands as rapidly as possible. It has, however, been observed that the operation times of the most commonly utilized LOM protection schemes can become dangerously prolonged when the power imbalance between production and consumption in the islanded network is not large enough. This is a major challenge for the utilization of fast automatic reclosing because all DG units in the feeder in question should be disconnected within the open time of the circuit breaker(s) performing the automatic reclosing sequence. The commonly used open times of fast automatic reclosing are from 0.2s to a couple of seconds which brings high requirements for LOM protection.

One option for fastening the operation of LOM protection is to make the LOM protection settings very strict. This, however, unfortunately causes unwanted tripping of the DG units which can even lead to system stability problems in power systems with high DG penetration. Strict LOM protection settings are conflicting with the FRT requirements because obviously DG units cannot support the power system during voltage dips if the LOM protection always disconnects the DG units when voltage dips occur. This conflict can be solved by using communication based LOM protection schemes because they are not based on measuring system quantities. Communication based LOM protection schemes can also provide rapid operation times and reliable detection of islanding. These methods are technically superior to passive and active LOM detection methods but also more costly. This makes communication based LOM protection schemes mostly attractive for large DG units, whereas, for smaller DG installations it may not be reasonable to spend so much money on protection. Passive and active LOM protection schemes will thus likely still have their own relevance. Some active LOM protection schemes are actually capable of detecting balanced islanding. Active methods, however, also have their downsides such as slow detection times and power quality issues. Passive or active LOM protection schemes are also usually used as back up protection for communication based schemes to make sure that some protection still exists if the communication system fails.

Intentional islanding can be used in many cases for increasing the reliability of power supply. For the use of intentional islanding, the LOM protection of the DG units which are attending to the intended island operation will naturally need to be either loosened or completely disabled. This readjustment of LOM protection can be quite challenging in case if the transition to the island operation is meant to happen without interruption because in this case the readjustment of LOM protection needs to take place immediately and automatically. This basically means that it is necessary to use some sort of communication based LOM protection scheme.

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9. ICT solutions for management of Smart Grids

Author: Antti Koto

SMART GRID VISION

What is Smart Grid?

Smart Grid (SG) is the power transmission and distribution network of the future. It supports all types of energy production possibilities from centralized production (e.g. nuclear power plants) to highly distributed generation using renewable energy sources (e.g. wind and solar power). Furthermore, the Smart Grid enables large scale commissioning of electric vehicles, increased reliability of power distribution, and improved power quality. From customer point of view, the Smart Grid makes it possible to reduce electricity bills by scheduling the use of energy based on real-time energy prices, receive financial compensation by taking part in demand response schemes, and make profit by selling energy to the grid.

From architectural perspective, the Smart Grid can be divided into three high-level layers: the physical power layer (transmission and distribution), the data transport and control layer (communication and control), and the application layer (applications and services) [Lee09]. Achieving the Smart Grid vision requires development of traditional energy and power engi-neering but even more importantly large-scale utilization of new communication interfaces and software applications (data transport and control layer). From information and communi-cation technologies (ICT) point of view, the most significant missing link in distribution net-works has been the communication between utilities and end-customers. Implementation of advanced metering infrastructure (AMI) will remove this problem and fulfill one of the most important requirements of the Smart Grid.

The ICT architecture of the Smart Grid has to be based on international standards which can guarantee the interoperability of different systems developed by different vendors. Stan-dards are needed for data transfer interfaces and information models as well as for communi-cation technologies. In some specific areas there are widely adopted standards already in use (e.g. IEC 61850 in substations), but there are still many domains where standards are under development (e.g. IEC 61968 for control centers) or where several different specifications compete against each other (e.g. BACnet, LON, ZigBee/HomePlug and Z-Wave in home automation).

In the USA, the National Institute of Standards and Technology (NIST) has chosen 75 most important Smart Grid standards in a publication released in January 2010 [NIST10]. These include standards made by different standardization organizations (e.g. IEC, ANSI and IEEE) as well as specifications made by different associations and consortiums (e.g. W3C, OASIS and OPC Foundation). In addition, International Electrotechnical Commission (IEC) has published its own

Smart Grid Standardization Roadmap [IEC10] in June 2010. Interoperability between different standards made by different organizations is one of the biggest challenges the electricity sector is facing in the future. Besides interoperable, the ICT systems of the Smart Grid have to be expandable and scalable, offer good performance and usability, and minimize the risks related to information security.

Why Smart Grid?

The most important driver for the Smart Grid is the environmental threat of global warming. In recent years this threat has resulted in a number of ambitious plans to reduce CO2 emis-sions around the world. For example, in 2007 the European Union set so called “20-20-20” targets meaning that by the year 2020 the greenhouse gas emissions should be reduced by 20 % compared to the level of year 1990, renewable energy sources should cover 20 % percent of energy consumption, and the use of primary energy sources should be reduced by 20 % compared with projected levels by improving energy efficiency. These targets were enacted to legislation in the EU area in 2009.

The three most important goals for the Smart Grid are the reduction of greenhouse gas emissions, improvement of power distribution reliability and power quality, and increase of customer choice and possibilities to save energy. Other Smart Grid benefits include new pos-sibilities for predictive maintenance, better resilience to disturbances, and enhanced capacity and efficiency of the existing electric power networks. From the distribution network point of view, achieving the Smart Grid vision requires new solutions in planning, building and opera-tion of the network, and also significant investments in new ICT systems (e.g. AMI).

From ICT point of view, the most significant benefits gained from new ICT solutions (i.e. standardization and advanced ICT system architecture) are the reduction of the total amount of data transfer interfaces in information systems, the acceleration of the commis-sioning of new information systems and business functions, and the clarification of the com-munication between network companies and service providers. All these factors reduce the maintenance costs of information systems and improve utilities’ ability to react to changes in business processes and business environment. Furthermore, new ICT solutions make it possi-ble to increase the number of information systems and data volumes significantly, which is a critical requirement for new applications such as large scale utilization of distributed genera-tion, electric vehicles, demand response and home automation.

SMART GRID IN FINLAND

The Smart Grid vision has to be adjusted to meet the local special characteristics. In Finland, these include cold weather, limited amount of solar radiation, long distances between cities, and large amount of medium voltage overhead lines in the countryside. These factors mean that solar power, electric vehicles and reliable weatherproof electricity distribution (i.e. re-placing medium overhead lines with underground cables) cannot be taken into use in large scale anytime soon. Therefore, the first version of Finnish “smart energy infrastructure” is more likely to be based on centralized nuclear, hydro and coal power plants, distributed wind and biomass power plants, hybrid vehicles having both electrical motor and combustion en-gine, new communication and control systems (e.g. AMI and aggregators for distributed re-sources), and new schemes (e.g. island operation) for providing reserve power to consumers during major disturbances. These applications can partly be controlled with currently existing ICT systems, but also new ICT systems are needed.

In Finnish distribution companies the level of automation and ICT systems in network operations is quite high compared to other industrialized countries. There are microprocessor based relays in substations (with and without IEC 61850 support), Supervisory Control and Data Acquisition (SCADA) systems in control centers, and reliable communication links be-tween control centers and substations (based on IEC 60870-5-101 & IEC 60870-5-104) in place in almost every one of the 89 distribution companies in Finland. Also Distribution Management Systems (DMS) are installed in most of the control centers and as a response to changes in national legislation in 2009 there are large AMI projects going on in most of the distribution companies.

RESEARCH OF ICT SOLUTIONS

What needs to be done to achieve Smart Grid vision?

From ICT point of view, the two biggest obstacles between currently used solutions in Fin-land and the Smart Grid vision are the lack of standardization and the lack of advanced sys-tems architecture that can support enterprise-wide applications. Without widely accepted standards, the devices and software applications developed by different vendors will not be interoperable. In addition, from Distribution Network Operator (DNO) point of view, the lack of standards reduces investment security. According to IEC, the core standards of the Smart Grid are [IEC10]:

- IEC 62357 Reference Architecture - Service Oriented Architecture (SOA)
- IEC 61970/61968 Common Information Model (CIM)
- IEC 61850 Substation Automation
- IEC 61968 Distribution Management
- IEC 61970 Energy Management
- IEC 62351 Security
- IEC 62056 Data exchange for meter reading, tariff and load control
- IEC 61508 Functional safety of electronic safety related systems

Some of the IEC core standards (e.g. IEC 61968) are still partly unfinished and therefore there are not yet standardized products on the market that could cover the needs of distribu-tion companies. For example, there is no SCADA or DMS products available with IEC 61968 standard interfaces. Furthermore, the harmonization between different standards (e.g. IEC 61970/61968 and IEC 61850) is still under progress. Besides core standards, IEC also offers a number of standards for the communication needs of the Smart Grid such as communication between substations and control centers, communication between different control centers, and communication of distributed energy resources, electric vehicles and smart meters. The IEC reference architecture based on these standards is attached to appendix 1 [IEC10].

Another key element besides standardization is the development of advanced ICT system architecture. Without sophisticated systems architecture, the management of the information systems becomes overly complex which results in poor performance, usability, scalability, expandability and security of the information systems. The most promising architecture model for distribution network companies is based on Service Oriented Architecture (SOA) [EPRI08, IEC10]. The essential principle of SOA is to implement information system functions as services which are available for all parties and applications that need them. These services can be owned and maintained by different parties and they are available regardless of the computer hardware, operation system, programming language and communication line used. In SOA the information systems are integrated by using loosely coupled connections which means that the information systems' dependency on each other is minimized. The ultimate goal of SOA is to improve the interaction between information systems and business processes and thus improve the automation and adaptability of business processes.

ICT is an essential enabler of the Smart Grid. It is needed in all parts of the network to ensure reliable and efficient operation of the Smart Grid. The most essential development needs related to ICT at different levels of the network can be listed as follows:

- Control centers and information systems in the office
  - Standardization
    - Information models
    - Data transfer interfaces
    - Communication technologies
  - System architecture
    - Implementation of Service Oriented Architecture (SOA)
    - Implementation of Enterprise Service Bus (ESB)
- Substations
  - Implementation of IEC 61850 standard
  - Implementation of substation SCADA
- End-users
  - Implementation of home automation
  - Integration of smart meters and home automation
- Communications
  - Standardized and TCP/IP based
  - Duplicated data connections to strategic targets (e.g. substations)

- o Data connections to Distributed Generation (DG) units
- o Data connections to Electric Vehicles (EV)
- o Information security

Current research themes worldwide

There is a vast amount of research going on globally around ICT and Smart Grid themes. A list of research themes related to ICT solutions in Smart Grids consists of at least the follow-ing subjects (with example papers about themes closely related to my own research):

- Information system interfaces [McN09]
- Information models [Lop10]
- Communication technologies [Ser10, Mer09]
- Coordination between standards [Pra09, San10]
- System architecture [Gir09, Pos10, Roh10, Kok09, Bre10]
- Information security
- Centralized vs. decentralized systems
- Data storage
- Real-time requirements
- Performance issues

Research related to information system interfaces deals mainly with parts 3-10 of the IEC 61968 standard and with MultiSpeak specification. Parts 3-10 of IEC 61968 specify interfac-es for different business processes used in distribution network companies such as network operation, records & asset management, operational planning & optimization, maintenance & construction, network extension planning, customer support, and meter reading & control. The standard is still partly unfinished. MultiSpeak is corresponding specification with IEC 61968 and widely in use in distribution companies in USA.

Information modeling is also mainly done by IEC. The most important information mod-els related to the Smart Grid are the Common Information Model (CIM) specified in IEC 61970 & IEC 61968, and the information model included in IEC 61850.

Communication technologies is huge research topic as it covers all different techniques how data can be transferred between different devices and information systems used in the distribution networks. From high level information systems point of view, the most interesting technique is Web Services which is based on platform independent technologies such as XML. On lower levels of data transfer there are numerous wired and wireless technologies available.

Coordination between different standards is crucial research theme as it is recognized as one of the biggest challenges the electricity sector is going to face in the future. The main research questions are related to harmonization of IEC 61970/61968 and IEC 61850 [Pra09, San10]. Also harmonization of IEC 61968 and MultiSpeak is researched [McN09].

Research of advanced system architecture is as well recognized as one of the top priorities in making Smart Grid a reality. The key elements of the next generation DNO system archi-tecture is believed to be based on SOA, ESB and CIM [EPRI08, IEC10]. From the rest of the research themes mentioned, one especially important is the information security.

Own research compared to research done elsewhere

The topic of my own research is information systems in distribution network operations. Sub-topics include standardization, data transfer technologies and system architecture. The target of my research is to develop a new model of information system architecture for distribution network companies based on international interface and information model standards and Web based data transfer technologies, and to demonstrate new applications to be used in the operation of distribution networks. In the future the information system architecture is ex-pected to provide better openness, expandability, modularity, scalability, performance, usabil-ity and security than the systems used today. In as traditional branch of technology as power distribution, achieving this requires a lot of work and a new way of thinking.

Information systems typically used in the operation of distribution networks in Finland are nowadays DMS and SCADA. Furthermore, DMS requires information from several other information systems including Network Information System (NIS), Customer Information System (CIS) and Meter Data Management (MDM) system. Also data transfer connections to other information systems owned by different parties like Transmission System Operator (TSO), other distribution network companies, service providers and different authorities are required.

The interfaces between information systems used in distribution network companies are nowadays company and product specific solutions customized directly between two informa-tion systems. This kind of integration strategy requires data conversions in each interface because there is no standard interfaces and information model in use. As a result, the system architecture becomes complex and difficult to maintain, as seen in figure 1. As information systems have lifetime of approximately 5 to 10 years, and the number of information systems increases as time goes by, the lack of open standard interfaces and common information model leads to increasingly burdensome and expensive integration projects and high ICT maintenance costs.

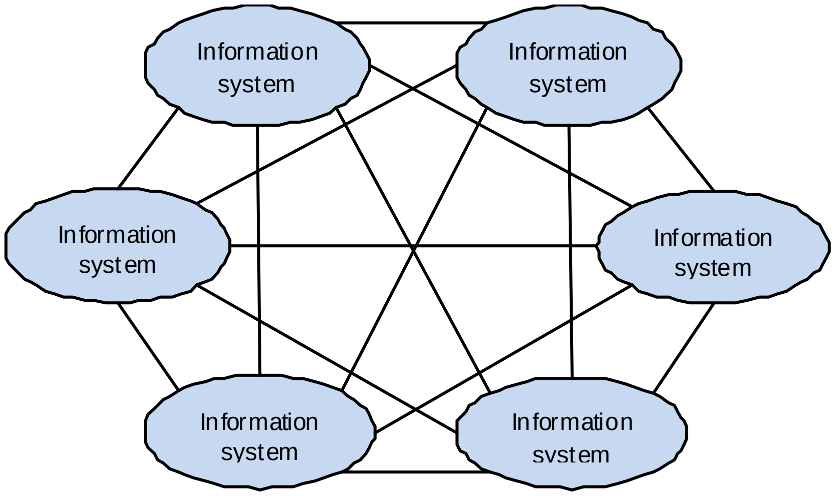

Fig. 1. Point-to-point integration method. Lines between information systems represent separate data transfer interfaces.

My M.Sc. thesis [Kot10] forms the basis of my research. In my thesis the best solution for future system integration was found out to be system integration through Enterprise Service Bus (ESB) using standard interfaces and standard information model, as shown in figure 2. The most promising candidate for the standard interfaces and information model is known as Common Information Model (CIM). The CIM consists of two IEC standards (IEC 61970 and IEC 61968) which are still partly under development. At the data transfer implementation level the most important technologies were evaluated to be the eXtensible Markup Language (XML) and Web Services (WS). The most significant benefits gained from the utilization of open standard interfaces are the reduction of the total amount of interfaces, the acceleration of the commissioning of new information systems and business functions and the clarification of the communication between network companies and service providers.

Compared to the research done elsewhere the research subject of my own research is nothing unique. Information systems in the context of distribution network operations are under research everywhere where the Smart Grid is set as the main target of distribution net-work development. Advanced information system architecture based on SOA, ESB and in-ternational standards form a common goal for studies carried out around the globe. What dis-tinguish my own research from work done elsewhere are the country-specific properties of Finland. Although the aim of my work is to use international standards and frameworks as much as possible, there will be differences in the final concepts developed in different coun-tries due to country-specific differences in legislation, culture, history and national energy strategies.

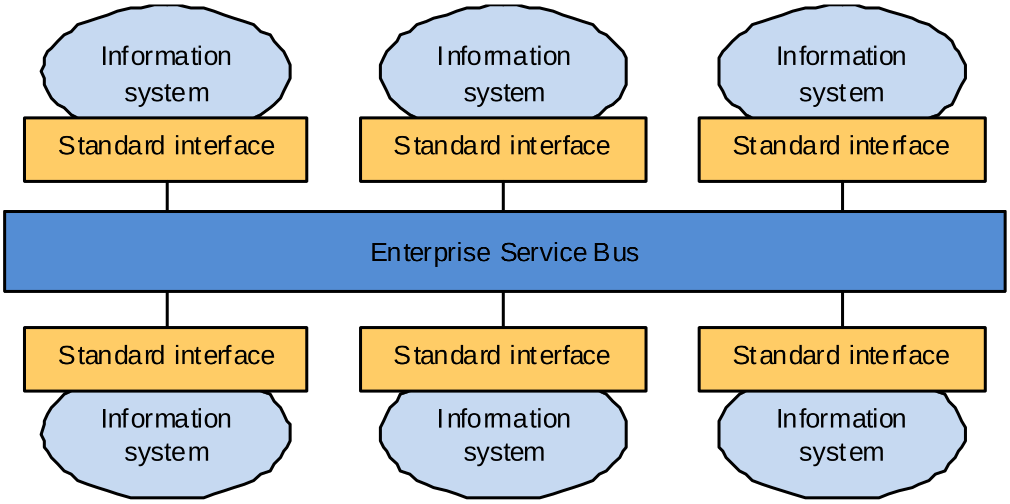

Fig. 2. Integration of information systems through enterprise service bus using standard in-terfaces. Inside the ESB a standard information model (e.g. CIM) is used.

Compared to the research done elsewhere the research subject of my own research is nothing unique. Information systems in the context of distribution network operations are under research everywhere where the Smart Grid is set as the main target of distribution net-work development. Advanced information system architecture based on SOA, ESB and in-ternational standards form a common goal for studies carried out around the globe. What dis-tinguish my own research from work done elsewhere are the country-specific properties of Finland. Although the aim of my work is to use international standards and frameworks as much as possible, there will be differences in the final concepts developed in different coun-tries due to country-specific differences in legislation, culture, history and national energy strategies.

CONCLUSION

The Smart Grid will revolutionize the way we use electrical energy. For distribution network companies this means implementation of new network planning and operation methods, as well as large scale utilization of new ICT systems. For the end-users, the Smart Grid means improvements in the reliability of electricity delivery and new possibilities for energy saving and home automation.

ICT is an essential enabler of the Smart Grid. Modern information and communication systems are needed, for example, in control centers, substations, distribution substations, dis-tributed generation units and end-user connection points. In Finnish distribution companies the ICT systems are relatively advanced compared to other industrialized countries. Distribu-tion automation based on microprocessor-controlled relays, SCADA and DMS information systems, AMI and IEC communication standards form a good starting point for developing the Smart Grid.

From ICT point of view, the two most significant challenges in making Smart Grid a reality are standardization and development of sophisticated system architecture. Currently there are hundreds of standards in use made by different organizations and a lot of new stan-dards are under development. Coordination between different standards is one of the biggest problems the electricity sector is facing in the future. According to IEC, the most important standards for the Smart Grid are IEC 61970/61968 for the control centers, IEC 61850 for substations and IEC 62351 for information security. In addition, there are several IEC stan-dards with high Smart Grid priority related to communication between different devices, ac-tors and parties in the electrical networks. Some of these standards are not yet ready so there is still a lot of work to be done before utilities can be using products based on these stan-dards.

My own research subject is closely related to the other significant development need of new ICT solutions - the system architecture. The most promising solution for the system ar-chitecture of DNO control centers is based on SOA, ESB and standardized interfaces and information model. The most significant benefits gained from new system architecture are the reduction of ICT maintenance costs, improved adaptability to changes in business environ-ment, and possibility to increase the information systems and data volumes substantially. This scalability and expandability is very important factor as the new applications (e.g. distributed generation) of the Smart Grid are likely to multiply the amount of data transferred and processed in information systems. As the significance of ICT in the electricity sector increas-es, also the information security becomes increasingly important.

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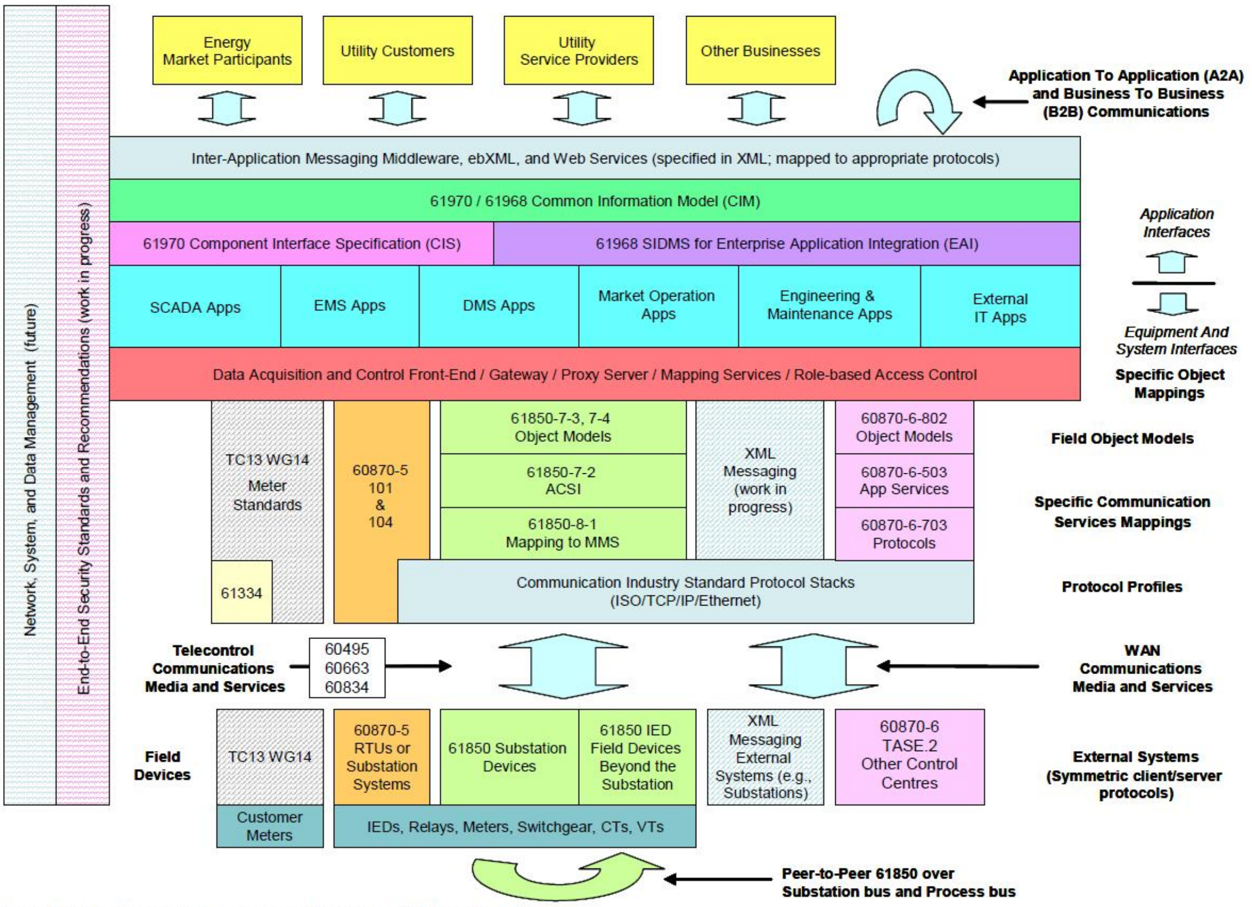
Appendix 1: IEC Reference Architecture



*Notes: 1) Solid colors correlate different parts of protocols within the architecture.
2) Non-solid patterns represent areas that are future work, or work in progress, or related work provided by another IEC TC.

10. ICT solutions for disturbances

Author: Heidi Krohns

DEFINING THE SMART GRID

The European Technology Platform Smart Grids defines smart grids as “electricity networks that can intelligently integrate the behaviour and actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.” Smart Grids deliver information and intelligence. Intelligence comes from the better use of technologies and solutions and better plan and run existing grids to control generation, enable new energy services and energy efficiency improvements. [1]

A Smart Grid will transform the way power is delivered, consumed and accounted for. Whit adding intelligence to grid reliability and power quality can be increased; responsiveness improved; efficiency increased; current and future demand handled. Handling current and future demand; reducing costs for the provider and consumer potentially and providing the communication platform for new applications can be also realized by adding intelligence. Smart Grid will connect IT and telecommunications markets to energy delivering. [2]

The biggest challenges that Smart Grid faces are interoperability of standards; utility business models that promote the energy efficiency and proper development of systems architecture to support enterprise wide current and future applications. [2] Developing the Smart Grid may have technical challenges with smart equipment, communication systems, data management, cyber security, information and data privacy and software applications. Smart equipment means all computer or microprocessor based field equipment. Embedded computing equipment has to be enabling to handle future applications many years without being replaced. To manage the challenge with communication systems Smart Grid has to accommodate new media as they emerge from the communications industries by preserving interoperable secured systems. Data management works well usually with small data amounts, but Smart Grid requires large amounts of data. Cyber security, information and data privacy will cause problems when various stakeholders will use Smart Grids communication systems. Privacy has to be secured by giving different user rights to information from Smart Grid. Requirements to applications are changing to more demanding. Applications must deliver results more quickly and accurately in Smart Grid. [3]

The Smart Grid consists of three high-level architectural layers (Figure 1); the physical power layer, the data transport and control layer and the applications layer. Layers contain transmission, distribution, communication, control, applications and services. Layers are divided into sub layers and detailed market segments. Market segments and applications include for example advanced metering infrastructure (AMI), energy storages, electric vehicles including smart charging and smart homes. [2]

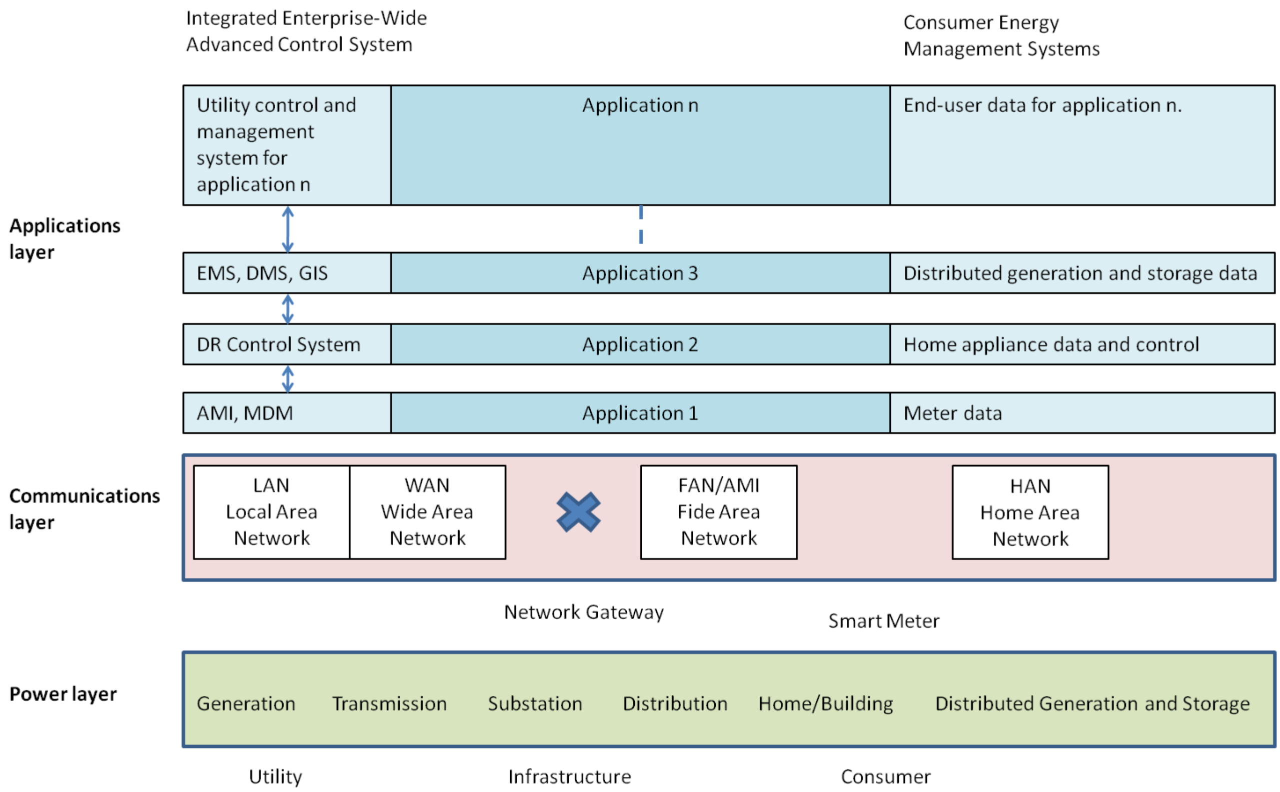


Figure 1 Layers of Smart Grid [2]

Smartness to the grid is needed to handle increasing renewable energy production. Smart Grid is needed to facilitate and integrate these variable generation sources. Energy storages could be used to support increasing distributed energy production. The advanced applications are expected to develop based on available current technologies and on the needs of the market. For examples charging electric vehicles likely will start from simpler associated applications, like smart charging, until the markets are ready to support more complex applications. [2]

Key Drivers to smart grid are growing energy demand, energy independence and security, greenhouse gases reduction, economic growth, policy and regulation, technology advancement, increased efficiency through grid optimization, advanced consumer services, infrastructure reliability and security and 21st century power quality. [2]

NIST [3] has divided the benefits to Smart Grid benefits and to stakeholder benefits. The Smart Grid will provide a reliable power supply with less outage. Grid will be more self healing because of use of digital information, automated control and condition based maintenance. The Smart Grid detects unsafe and insecure situations to secure its reliability. Smartness will reduce total energy use, peak demand and energy losses. That way it will increase efficiency. By supporting renewable energy sources, by using more effective energy sources and electrical vehicles Smart Grid will reduce greenhouse gases. Direct economic benefits will come from by reducing operations costs. Customers also will have more pricing choices and access to energy information. [3]

Stakeholder benefits can be divided into benefits for consumers, utilities, manufactures and society. Consumers will have ability to balance their energy consumption with the real time supply of energy. The Smart Grid will support installing the infrastructure of the consumer. Benefits to utilities are ability to provide more reliable energy, especially in emergency situations. They can also manage their costs more effectively through efficiency and information. Manufactures produce all new components to the Smart Grid. It will increase opportunities for new business developments and existing business enhancements. The Smart Grid helps society to get more reliable power supply. It can help governmental services, businesses and consumers sensitive to power outage. Benefits to some stakeholder can also change to benefits to other. [3]

INFORMATION SYSTEMS AND OUTAGES IN SMART GRIDS

In outage situations, rapid decision making is needed. At present, the operator gets information from a variety of sensors. This does not support acting on in the necessary timeframes to minimize the impact of a disturbance. Selected islanding is one way to minimize the consequences of an outage. This action can be provided by power system information services. Scenario development in addition to quantitative statistics, trends and forecasts could provide estimating the socio-economic impacts of outages. Services should be available in a Geospatial context. [4] To secure and stable operation on temporal spectrum, it is demanded to develop new decision support tools that include actionable intelligence in the required timeframe. [4, 5] King [4] and Sebastian et al. [5] suggest new information systems to resolve the problem.

King [4] suggests the automatic pilot power system concept (Figure 2).

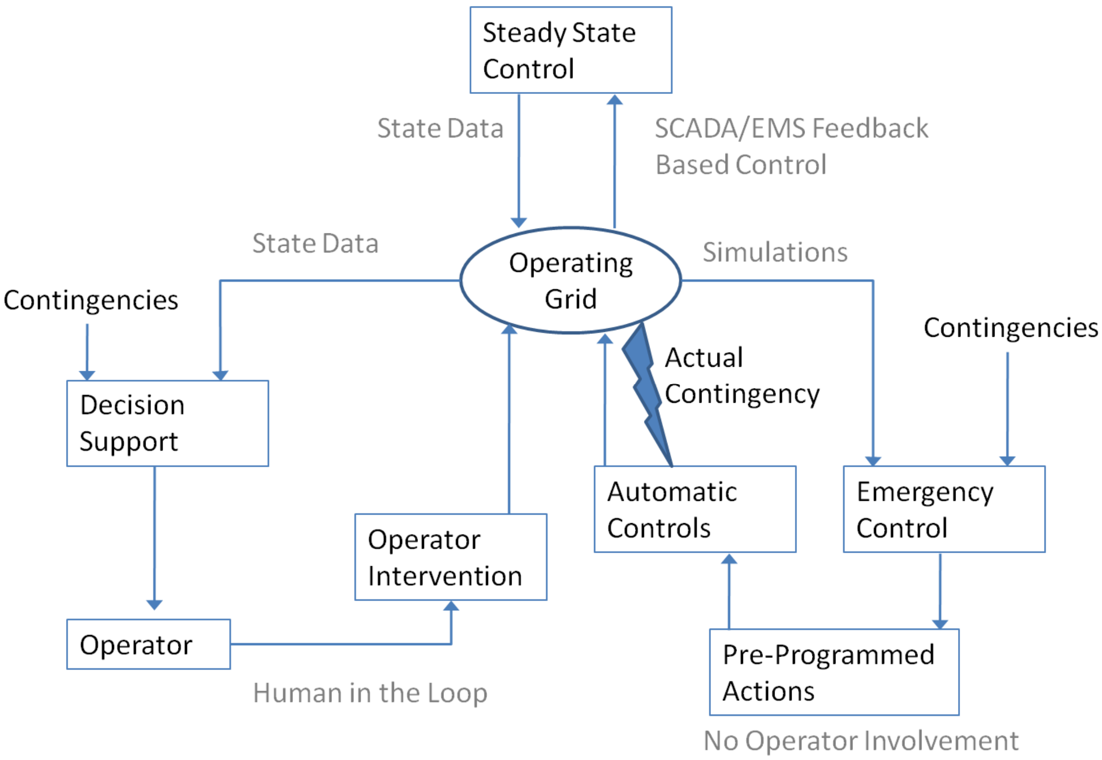


Figure 2 Automatic pilot concept. [4]

Several services have to be interconnected into a multi agent system to support auto-pilot operation as an emergency control, restoration control etc. [4].

At the present, the power system operation environment consists of many distributed tools and components. The interfaces of these components have to be standardized to work with the hardware of the substation automation. The present applications use a different format or different system topology level of details based on different applications. Power companies use similar applications from different manufacturers. Heterogeneity is important to the exchange of data among the various services necessary for the auto-pilot. Next individual services should be integrated so they could perform more complicated functions. To realize integration, change must start from the data and information level. The data model should be standardized. Between software shared data and information should be clear and precise. Terminology should be standardized and taxonomies for ontology drives decision support tools for the electric grid should be developed. Heterogeneity problems must be solved so that the middleware provides tools for browsing and for accessing the data resources. Middleware generally means any programming that mediates between separate and often already existing programs. It is used to hide the heterogeneity of the underlying components or applications and provide uniform access to their functions. [4]

By varying characteristics of the sensor network constrains the seamless access to the real time data. Reconciliation of the syntactic and semantic heterogeneities in the data influence solves these problems. There has been proposing to develop syntactic standardization. Also Several metadata standards have been developed world-wide and are now widely accepted as the standardized models for data and metadata. Information entities can only be completely understood within its context. Ways to preserve the contextual information in the translation process have to be found. Standardization of metadata as advocated by multiple organizations has resolved some problems with the syntactic heterogeneity. To guarantee meaningful data sharing semantic reconciliation is necessary. [4]

Sebastian et al. [5] suggestion is a situation awareness tool. The data coming from the substation does not give enough accurate picture of the whole network. That end-user could get an accurate real-time view of the network a situation awareness tool is needed. The tool gives calculated information that user can use to prepare the next operations. [5]

Situation awareness tool includes (Figure 3):

- Distribution System Estimator,
- Situation Awareness Core,
- Contingency Analysis,
- Alarm Log,
- Load Profiles,

- Day Ahead Operation Planning,
- Solution Module,
- Solicitation of Reserves or Reconfiguration.

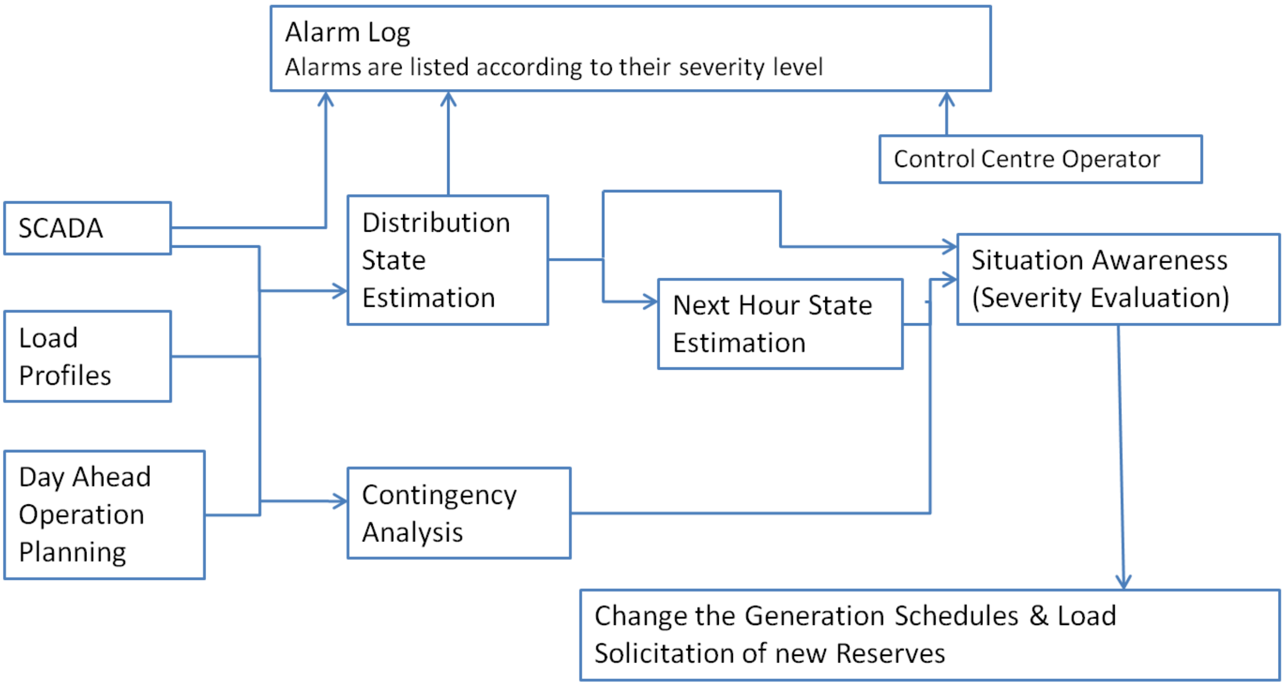


Figure 3 Situation awareness tool [5]

The tool allows observing the flows and the voltages evolution in the next hour. It allows the operator run an application to solve the potential problems. The application recommends different possibilities to handle the situation. The tool highlights the critical parameters and values, raise alarms when needed and propose solutions in order to help the operator cope with difficult situations and manage priorities. [5]

The connected communication system of the smart grid has to be able to cover all kinds of power plants, different levels of power networks and power supply companies, different types of new energy power generation industries, the majority of electricity users and the relevant industries of the power system. [6]

COMMUNICATION BETWEEN ACTORS IN MAJOR DISTURBANCES

Storms like Pyry and Janika in Finland in 2001, and Gudrun in Sweden in 2005 and Asta, Veera, Lahja and Sylvi in 2010 in Finland were storms, where some individual customers were left without electricity for a few weeks. In Finland, is studied how to develop recovery from major disturbances by developing the communication between actors. Krohns et al. [7] defines the major disturbance in the supply of electric power as a long lasting or widespread interruption in the supply of electric power, during which the fire and rescue services and one or more other public actor (municipality, police, etc.) need, in addition to the distribution network operator, to start implementing measures for reducing possible severe consequences to people and property.

The information systems of the Emergency Response Centre (ERC) can be used as a good example of systems that can be used to connect many authorities. ERC is also connected with most cases in major disturbance in the supply of electric power, because they deliver missions to authorities. Fire and rescue services are the most common partner to DSOs in major disturbances. The Finnish Defence Forces can have a major role in disturbance through the executive assistance. They have lots of special equipment and skills to act in disturbance situations for example after storm. Other actors can be police, municipalities, the Finnish Meteorological Institute (FMI) and the special health care. [7]

At present DSOs communicate with other actors mainly with using a mobile phone and landline phone. That can be insufficient for example in storms mobile phone networks may not work all the time. Some DSOs also use satellite phones which are not disturbed because of storm. However, a phone call does either not include enough information. This present systems do not support this communication between actors in major disturbance. [7]

There has been created a model about communication between actors in major disturbances in the supply of electric power. Figure 4 presents the model. Communication at the present is shown with blue lines and the future situation with red lines. Communication is divided into emergency situation and to the situation of disturbance in electric power supply. At present, communication between emergency authors and DSOs consists of communication between some fire and rescue services and DSOs. At the moment Municipalities and critical customers are left out of communication in disturbances. FMI gives warnings to DSOs and fire and rescue services. [7]

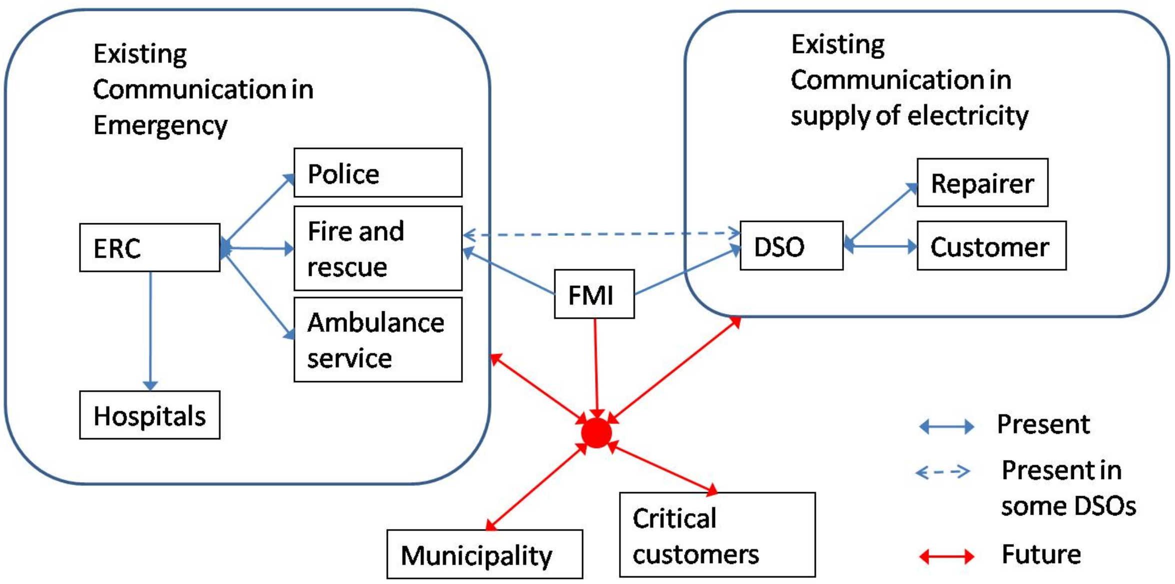


Figure 4 Communication between actors [7]

There could be more communication between DSOs and emergency authorities, in major disturbance in the supply of electric power. Also municipalities could be added to this communication. There should be communication also between other actors and critical customers or the special health care. FMI's information could be delivered to all actors. Increasing the communication would increase a number of information lot because the number of the actors in major disturbances is large. [7]

The result of a questionnaire for DSOs was that they want developing communication between actors in major disturbance. Developing communication between information systems was less needed, but is still considerable. Results to question about use cases was that information about long lasting or widespread disturbance should deliver to other actors. Other data, which DSOs wanted, was storm and snow forecasts. At present this information is not received straight to information systems. The use case answers may have been influenced because respondents come from DSOs. The same questions should be asked also to the other actors to get more precise results. Results from the questionnaire support the presented model of the communication between actors. [7]

This study suggests a common operational picture system to be one solution to develop the communication between actors. The system could help actors to get information about situation and others actions and could work in between actors' present systems as an interface. Incompatibility between information systems is kept as a challenge if developing communication between systems is started. DSOs already have a problem with unattached systems because of several different information systems they have. In major disturbances, actors come from many different organisations, which all have different information systems. That can cause compatibility with other actors systems. DSOs are also concerned that new system would bring too much work strain to operators. The work strain will increase, if there comes more systems interacting with present systems. That user interface could be the same for all systems; the new system should be integrated into present ones. [7]

CONCLUSIONS

The Smart Grid will increase the amount of the information in the electricity supply. At the presents, DSOs have similar applications from different manufactures. These applications use a different format or system topology level of details based on different applications. Decision making in disturbances is fast and need lots of information. Disassembled information will complicate the decision making. To efficient decisions, heterogeneity to the exchange of data among the various services is important.

There are a few suggestions to develop ICT and communication in major disturbances. In common to all suggestions is that the information should be combined to one system that mediates all required information to the operator. They also suggest that the terminology and data models should be standardized. Common to these results is also that information should be given in Geospatial form.

All the studies agreed that there will be problems with the compatibility of the systems. Present systems do not support communication between DSOs and other actors. They already have problems with only DSO’s own systems, so giving information to others will be challenging. One of the challenges of the Smart Grid was cyber security and information privacy. If this challenge will be solved, the Smart Grid can also solve some of the problems of communicating with other actors.

My own study is concentrated mainly on communication between all actors in major disturbances likewise others are studying mainly DSO's own communication. In future, a more precise model of the common operate system that could be used in communication between all actors should be created. There should be more studying about communications outside DSOs.

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11. Smart Grids – uninterrupted supply of electricity for customers?

Author: Janne Stranden

SMART GRID

In brief, term “Smart Grid” (SG) basically means new innovations and technologies that are aiming at transforming the present-day electrical energy system digitized and more intelligent. It is a system of many systems, each with own architecture. To execute this transition very high rate of utilization of communication systems are needed. This is required because intelligence herein usually means automatic solutions (e.g. monitoring, computing, reacting), and components used in these solutions need good communications to operate properly. Thus, the operation of SG is more or less as dependent on the reliability of communication networks as electricity networks. [1-4]

In [5] has been successfully compared SG with a smart person. Firstly, a person receives information via his/her senses. After considering this information a person will make a decision. Then he/she will take an action. Consequences caused by these actions will be observed and will increase the experience. Information about actions and analyzed experiences may be delivered to other persons as well. To make smart decisions a person needs good information about situation and knowledge about the consequences of actions. Figure 1 illustrates this process.

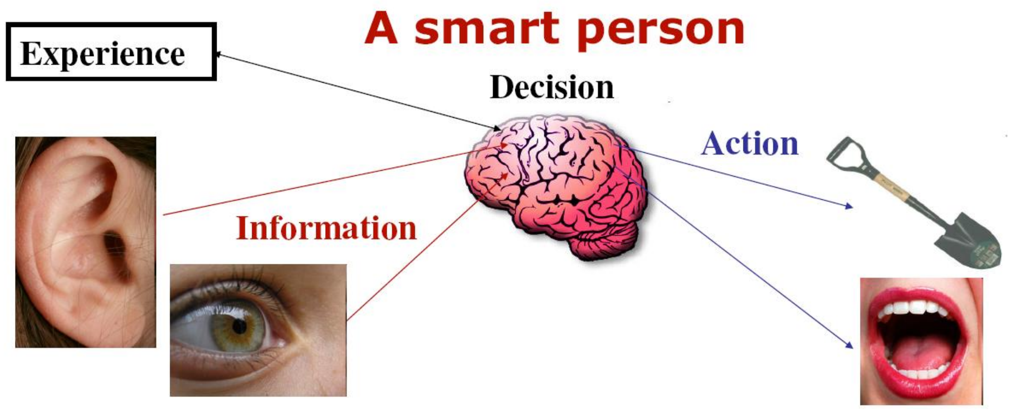

Figure 1. Operation of a smart person. [5]

Comparison between SG and a smart person is reasonable because the similarity of these systems is considerable: Also in SG good information is needed to make smart conclusions, decisions and actions. Based on experiences useful operations models should be created in order to make the decision-making easier in the future. As a smart person does, SG as well spreads the founded conclusions to other grids. [5]

Targets

The main goals of SG are for example: improvement in energy efficiency, base for renewable and distributed power generation, (consequently) reduction of greenhouse gas emissions, new market place and business models for more actors than nowadays, new services for customers and from this study point of view the most important, increase in reliability and power quality. The latest mentioned target means that customers will receive more uninterrupted electricity that is also high-quality. This will be very important improvement because nowadays the different functions of society are very dependent on electric energy and this dependence is still increasing as technologies develop. [1-5]

In order to reach better reliability of the power supply many solutions of SG have been introduced worldwide. The most optimistic scenario is that the grid will be self-healing, i.e. it can restore and prevent outages independently. Consequently, end-users would receive rather uninterruptible supply of electricity in that case. However, more realistic vision in the near future would be for example possibilities to operate a part of the network as an island in the case of disturbance if any (distributed) generation and/or energy storages are available. [1-4]

Challenges

Due to vast of new solutions included in SG, the grid will be much more complicated in the future. This complexity itself is a big risk although one object of SG concept is above mentioned self-healing. Of course, one big challenge is the transition to SG when already existing and new equipment should operate together, while newly installed components might have problems on their own operations. Especially it will be challenging to get the power flows move in two directions on the system that has been designed to be unidirectional. These changes in the grid environment should be anticipated carefully and in coordinatedly. [1; 3-4]

As the amount of intermittent energy sources, like wind and solar power, increases importance to balance demand and production will increase. In some cases emergency demand response, which means curtailing the power of defined consumers, will be an obligatory measure. [1; 2-3]

As said, the functionality of the communication system is somewhat equally important as the

functionality of the power system. Thus, getting great amount of this kind of systems to talk together will be challenging. Moreover, when the flows of information increase the importance of data and privacy protection will increase as well. Installation of millions of sensors and smart meters substantially increases the number of target points that could be vulnerable to cyber attacks. On the other hand, thanks to online monitoring these attacks could be noticed automatically and faster than before. [1-2; 4]

In addition to mentioned technical and also economic challenges, one big challenge to overcome is regulatory barriers and disincentives that slow down the development of this “dump” grid towards the smarter one. These regulations may already be dated in some cases. [1]

INTERRUPTION CRITICALITY OF CUSTOMERS AND SMART GRID

It is obvious that the electrical equipment and operations of different customer types of distribution networks vary much from each other. Thus the dependency on the supply of electricity could be rather various among different customers: while someone's operations may suffer a great deal from interruption even shorter than one second (e.g. industry and hospital), another may stand without electricity for several days (e.g. households). Consequently, it would be reasonable to take this interruption criticality of different types of customers into account when prioritizing restoration actions after disturbances and also in network planning.

Above has been mentioned how the new solutions of SG will decrease the amount of interruptions experienced by end-users. Self-healing, possibility to operate as an island with the help of distributed generation and energy storages, etc. better the reliability both on average and also may reduce the amount of interruptions experienced by those more critical customers. One but maybe not that realistic vision is that supply of electricity will be uninterrupted from customers' point of view. However, because there will be interruptions also in the future, the interruption criticality of the customers should be determined, this information should be used to create a model about the criticality and naturally these models should be utilized somehow.

Determining and using criticality information – challenging process

There are some challenges regarding using the criticality information and prioritization of customers connected to network. For example, the Finnish Electricity Market Act [6] states that distribution system operator (DSO) should secure the supply of sufficiently high-standard electricity to its customer by its own operations. On the other hand, in the Act and in its preambles, it has been emphasized the impartial and non-discriminatory treatment of customers when considering connection conditions and technical requirement, sale prices and the terms of system services. This may be easily understood that the reliability of the power supply should be equal for every single customer of the network. However, for example in [3] has been envisioned that in the year 2050 the prices and reliability (from the grid) may vary from region to region depending on done system service agreement. Before this stage, the Electricity Market Act should have been reformed to allow this.

As mentioned, in SG the flows of information will increase and thus the importance of data and privacy protection will increase as well and increased number of target points could multiply the vulnerability to cyber attack. Privacy protection will turn even more important if the criticality information of customers will be used in the future. In some cases it might be problematic to give confidential information about customer's operations even for DSO.

Determining the interruption criticality of customers is a very complicated process: What is the real critical interruption time for customer's operation? How the consequences of interruptions should be valued, i.e. why someone is more critical than another? Should the reserve power and other preparedness of a customer taken into account when prioritizing customers? One problem of determining and using interruption criticality information is also the responsibility issue: Who is responsible for determining the interruption criticality of customers, and who will maintain and update this information? In [7] is presented that not customers themselves or utilities (DSOs) but the municipalities and/or authorities responsible for certain field should execute the determination process.

Modeling interruption criticality

Nowadays some models to describe the interruption criticality of customers are used. For example, in Finnish regulation (for DSOs) there is a model in which two interruption cost parameters have been given based on customer’s power and energy consumption (€/kW and €/kWh). This model is linear and the criticality depends directly on the consumption of a customer: the bigger consumer of energy a customer is, the more critical for interruptions it is. [8] Another model is the legislative standard compensation practice that models a customer’s criticality as stepwise increasing function. Again, the criticality (the amount of compensation) is directly based on the consumption of a customer. [6]

Some new models have been introduced recently. Customer dissatisfaction index (CDI) was introduced in 2007 in [9]. In [10] two different satisfaction criteria have been presented: one for domestic customers and one for important customers (industry, hospitals, nursing homes, supermarkets, et cetera). Threshold values have been defined for the amount of annual interruptions and for the duration of an interruption. Another model has been presented in Finland in 2010 [11]. The new supply reliability criteria will be used as planning criteria by the DSOs. The criteria cover cumulative sum of duration of long interruptions and number of short interruptions (less than three minutes) experienced by a customer per year. In the new criteria, different customers are not classified according to their importance but according to their location. Customers will be divided into three groups: city, urban and rural area customers.

The models for the interruption criticality of a customer presented above, have all some pros and cons. Solution for improving the criticality model is to combine the best parts of each model. In figure 2, a new criticality model is introduced illustrated in parallel with the model used in present regulation (solid line). [7]

All different types of customers should have their own specific model that would contain initial criticality value, critical duration, and slopes before and after the critical time. In order to make the models even more accurate, the effects of different circumstances and point of time should be included in these models because in some cases the critical duration varies very much depending e.g. on the temperature outside and which day it is that time. [7]

Utilizing criticality information in future in Smart Grid environment?

Nowadays (in Finland) the determination and using of interruption criticality information are executed by DSOs. The whole process is internal. In [7] it is presented a proposal for utilizing the criticality information more effectively in the first place in the current state of (“dump”) power system. Figure 3 illustrates the procedure.

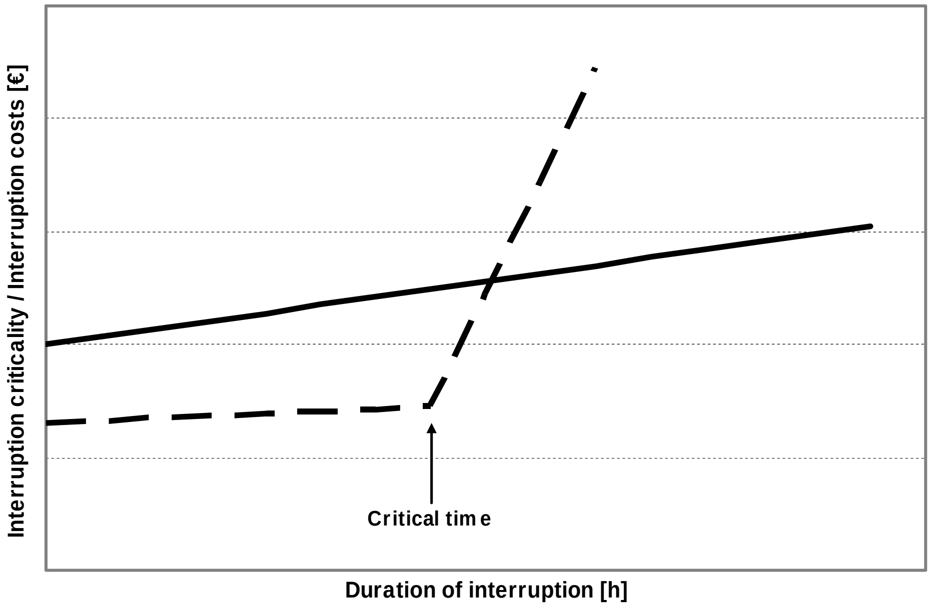

Figure 2. New interruption criticality model (broken line). [7]

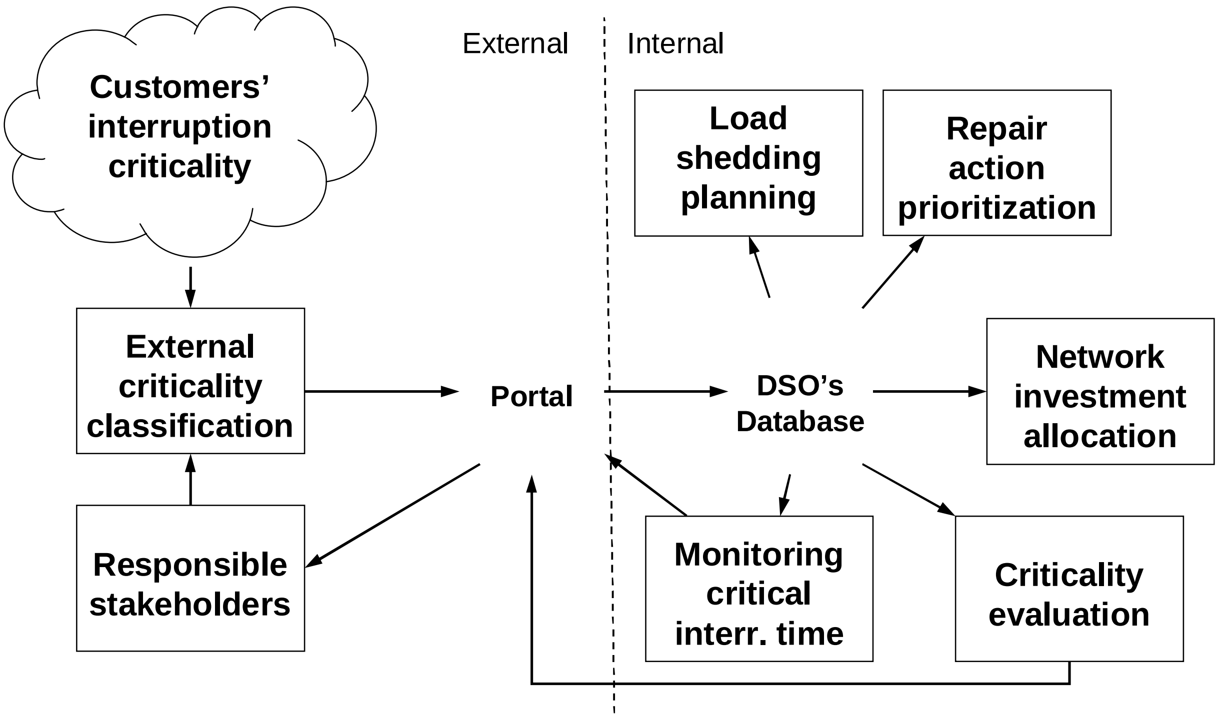

Figure 3. Flow of information about the interruption criticality in the future. [7]

The renewals of this proposal comparing to the current state are that the criticality information is determined externally from DSO's point of view, DSO execute some calculations and simulations to evaluate the criticality of these customers, and finally this information is delivered back to responsible stakeholders via portal. This kind of portal is under development, and it will be a common operational picture system between several actors that operate in the major disturbances of electrical power supply. Basics of the system are presented in more detail in [12]

How could this kind of procedure be related to SG? A good operational picture of the grid has been mentioned very important element for the correct operation of SG. By analyzing the current state of the system the future could be estimated better and responses would be faster [2; 4]. In order to have a good operational picture all the data systems should interoperate correctly. In the future when Advanced Meter Infrastructure (AMI) penetration increases the data about customers will be more specific and also disturbances in low voltage networks can be detected. AMI will also allow more sophisticated load shedding strategy for the power shortage situations because the obligatory curtailments could be done more selectively based e.g. on customer group or single operations, not on the areas or feeders as nowadays [4; 13].

Because of increasing amount of intermittent production behavior of customers' power consumption would be useful to know to estimate the balance between demand and production. Similarly, the criticality model of a customer should be stored into a database (of the smart meter or whatever) in order to make the prioritization of customers easier. [3] This model could also involve the parameters that represent the effect of circumstances and point of time on criticality. For example, a dialysis patient (home care) is very dependent on electricity during the dialysis process, but at other times not at all that interruption critical.

CONCLUSIONS

The visions about Smart Grid seem to include the idea of uninterrupted of electricity for customers, at least when talking about long-lasting interruptions. It also seems to be axiomatic that whole the power system will be built by underground cables. This kind of weather-proof system is needed in order to make e.g. self-healing and operating as an island possible at least in the cases of storms that are the most common reasons for long interruptions in distribution networks. On the other hand, when the whole distribution network is underground storms should not have any effect on it.

The intermittent nature of new power generation solutions may leads to situation in which the demand exceeds the production. As well as in disturbances, the supply to customers may be secured with the help of electric vehicles or energy storages when curtailments are needed or the grid connections are unavailable. Even though these "interruptions" may be quite short in many cases the information about customer criticality should have been determined in advance so that prioritization of customers could be done.

Generally most of the nearest future solutions of Smart Grids seem to aim at cost and consumption efficiency. Automated operations, such as self-healing, will not be realistic in a year or two. Moreover, all the overhead lines will not be changed to underground cables soon because it would not be very cost-effective. Consequently, there will be disturbances in the networks caused e.g. by storms and thus to recover from these situations actions done by real human beings is needed. Therefore my/our study of utilizing the interruption criticality information to mitigate the societal consequences of interruption is very relevant.

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12. Role of FACTS devices in high voltage Smart Grids

Author: Pasi Vuorenpää

INTRODUCTION

Increased energy efficiency, more effective utilization of existing system capacity and at the same time increasing or at least maintaining the existing level of reliability can be considered as few of the main targets in developing the electrical networks of the future, in other words Smart Grids. In general, some of the main measures to accomplish these targets are to improve the awareness of the system state with advanced measurement and monitoring, to increase the controllability of the system and to enable fast reacting to constantly changing operation conditions of the system. However, despite these targets and measures can be seen common for both, distribution and transmission level systems, practical realization of these objectives require system specified solutions. Therefore, reviewing the basic characteristics of Smart Grids in distribution and transmission level systems is usually executed separately. However, despite these distinct differences, in a way, Smart Grids can also be considered to bring these two systems closer to each other due to some common Smart Grid related applications affecting the operation of the both systems.

For instance, maybe the most well-known development area in aiming towards more intelligent distribution level systems is the Automated Meter Reading (AMR) technique and its various applications, which will enable two-way distribution of both energy and information flows in the distribution level system. Respectively, few examples of Smart Grid applications in transmission level systems are synchrophasor measurement and its various applications related to improved monitoring and control of the system and Flexible AC Transmission Systems (FACTS) devices, which will most likely become more popular in improving the controllability and thereby overall stability of the transmission level power systems. Moreover, distributed generation, distributed storages and microgrids are few of the examples of applications, which will have positive contribution to operation of the both distribution and transmission level systems.

In this paper short introduction to present state and future prospects of Smart Grids in high voltage power systems are presented. Thereafter, as an example of transmission system level Smart Grid applications role of FACTS devices in high voltage Smart Grids is discussed in more detail. It is concluded that more comprehensive utilization of FACTS related technology in high voltage power systems could be seen highly beneficial in the future, when more effective utilization of the existing system capacity and increased controllability of the system will be demanded.

ELEMENTS OF HIGH VOLTAGE SMART GRIDS

Despite the main objectives of Smart Grids are clearly specified in various publications the basic tools enabling the change especially in case of high voltage power systems are seldom examined comprehensively. In [1, 2, 3] visions and applications of transmission level smart grids are discussed in detail. Moreover, for instance The National Energy Technology Laboratory (NETL) the RealiseGrid project have identified promising technologies to increase the intelligence of the transmission level systems. [4, 5] The NETL categorizes the tools to five separate Key Technology Areas (KTAs) with relatively wide perspective including both existing and pending technologies. [4] These Key Technology Areas are named as Advanced Control Methods, Sensing and Measurements, Advanced Components, Decision Support, which all are dependent on fast and reliable Integrated Communication environment. Main characteristics and possible application examples related to each of the KTAs are listed in Fig. 1 and discussed briefly in the following subchapters.

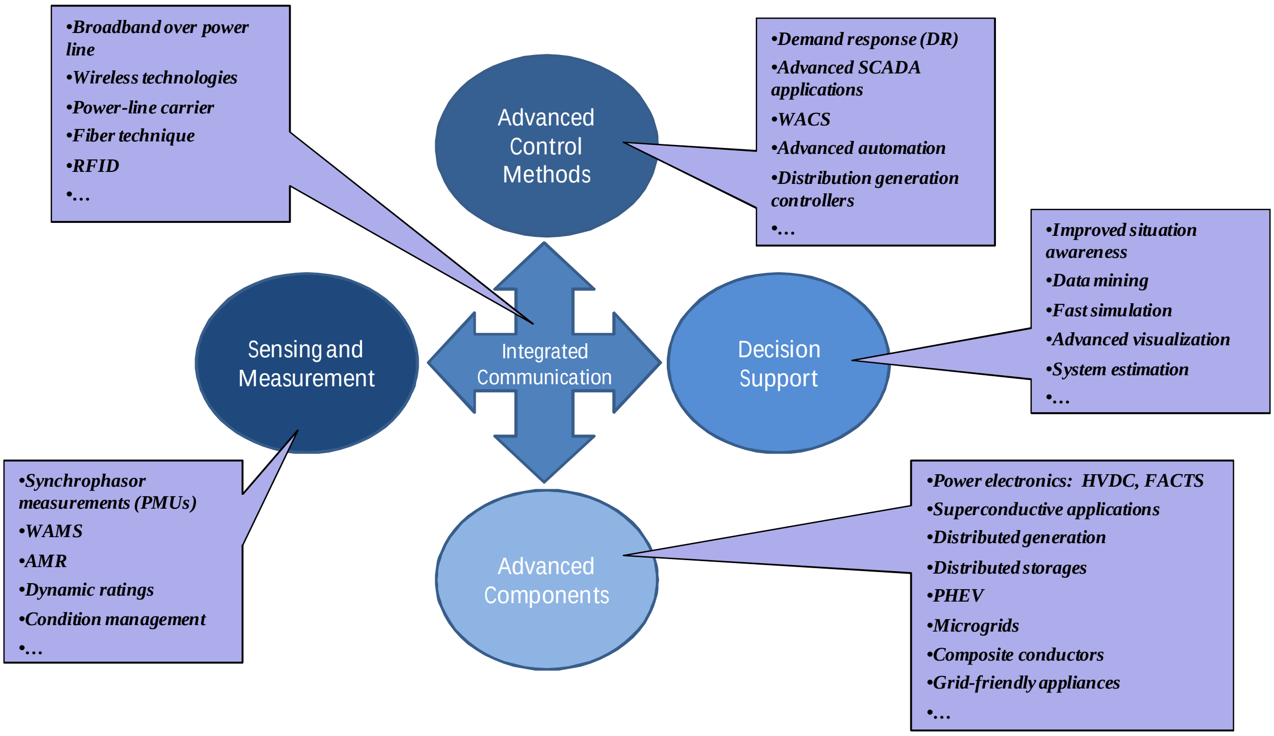


Fig. 1. Key Element of Transmission level Smart Grid by the National Energy Technology Laboratory (NETL)

A. Integrated Communication

One of the key elements in enabling more intelligent utilization of existing power system is to provide possibility for fast and reliable communication between individual components, monitoring systems and operators of the network. Despite the fast development of communication technology in past few decades, careful assessment is still required in selecting the applied communication techniques for power systems because of the high reliability requirements of the applied technology. Moreover, lack of comprehensive international standards regarding power system related communication applications have also delayed the wide utilization of modern communication technologies in the field of power systems. However, demand for sophisticated

Integrated Communication systems could be seen obvious to enable full utilization of many of the proposed Smart Grid features, which relay on fast and reliable communication between the different components and systems of the network.

B. Sensing and Measurement

Traditionally, operational management of the transmission level electrical systems has been based on measurement data, which is updated only at intervals of few seconds. However, to provide relevant information of the system state for purposes of the more intelligent system management, accurate real time data of the system quantities is required. Synchrophasor measurement and its various applications offer effective tools to fulfill this sensing and measurement task in real time basis. [6, 7] For instance, wide-scale utilization of the synchrophasor technique providing synchronized and real-time measurement data from the system could be utilized to ensure the stability and reliability of the system in more advanced manner.

In addition to measuring the system state more accurately also new applications such as dynamic ratings and advanced condition management could be included in sensing and measuring related Smart Grid applications. For instance, dynamic rating of the power system components is based on the fact that traditionally almost all of the system components are rated taking into account only the worst possible loading scenario. However, this approach usually leads to situation, where the components are loaded well below their actual overloading limit, which could be dependent on e.g. the ambient temperature. Thereby, dynamic ratings could enable full loading of the system component by taking more comprehensively into account the variables affecting the actual loading limits of the component. Advanced condition management again can increase the reliability of the system substantially through online condition monitoring and thereby estimating the optimal maintenance periods for the components and thereby preventing unexpected failures of the components.

As a conclusion, one of the main challenges related to wide utilization of advanced sensing and measuring applications is the excessive need for processing of the generated measurement data. Despite the significant increase in amount of real-time measurement data from the system it should not complicate the execution of the required operational measures. Basically, in the future, more advanced decision support techniques and control methodologies are required to enable effective management and operation of the system despite the increased measurement data available from the system.

C. Advanced Components

Despite various technical advancements in transmission system level components in recent years, so far economical and reliability concerns have slowed down the wide-scale implementation of many of these new components into real power systems. Therefore, significant potential is related to wider utilization of these new advanced components in practice. For instance, even though power electronics based solutions such as High Voltage Direct Current (HVDC) transmission or FACTS devices have already been applied in many of the modern power systems, more comprehensive utilization of their capacity together with other Smart Grid related features will help the transmission system operators to meet the Smart Grid related objectives more effectively. Role of FACTS devices in the Smart Grid evolution is discussed in more detailed manner in following chapters of the paper.

In addition to various advanced components dedicated only for high voltage level systems, also the distribution level advanced components and applications such as electrical vehicles (EVs), large-scale distributed generation, distributed storages, micro grids and virtual power plants will have an effect on the operation principles of the transmission level system. Despite concerns related to stability effect of these components in transmission level system they could definitely have also a strong positive contribution to the performance of the transmission level systems in the future. For instance, large amounts of EVs connected to grid are estimated to affect significantly the loading profiles of the system, in the worst case resulting temporary overloading conditions in the system. On the other hand, EVs connected to the grid could also be treated as a virtual energy storage, which could be utilized to balance the variability in the production and consumption of the electrical energy.

Despite one of the main objectives of smart transmission grids is to increase the capacity of the existing transmission system, also investments to totally new transmission lines are required for example in order to replace the out-of-conditioned lines with new ones. At the same time transmission capacity of the line can be updated to meet better the increased demand of electrical energy in the future. In this sense, new composite materials and superconductive transmission systems will offer totally new possibilities to arrange the electricity transmission in a more economical manner. [8] However, so far the investment costs have not been low enough to enable large-scale utilization of these new transmission techniques and e.g. based on the survey of RealiseGrid project, many of the TSOs in Europe are not considering the superconductive transmission systems among promising Smart Grid technologies at the moment. [5] Thereby, HVDC transmission can be seen the main development branch related to long-distance and large-scale electrical energy transmission systems in the future.

D. Advanced Control Methods

As mentioned earlier, technical developments in applications related to Measurement and Sensing and Advanced Components together with Integrated Communications enabling real time communication between these applications will open totally new possibilities to manage, control and protect the existing power system. Based on the Smart Grid definition of the NETL Advanced Control Methods refers to all sophisticated control methods and applications related to more advanced management of the transmission level power systems.

However, despite the various new control possibilities offered by the wide range of Smart Grid related applications, implementation of the new advanced control methods should be performed with careful assessment to avoid undesired interactions between different control systems and to ensure the sufficient reliability of the applied implementations.

The NETL has categorized the Advanced Control Methods into three separate themes: Distributed Intelligent Agents, Analytical Tools and Operational Applications. (Table I) Each of the themes describes existing and pilot stage applications of the Advanced Control Methods. Additional information regarding these themes can be found from [4].

TABLE I

Distributed Intelligent Agents	*Analytical Tools*	*Operational Applications*
• Digital Protective Relay • Intelligent Tap Changer • Dynamic Circuit Rating Tool • Energy Management System • Grid-friendly Appliance Controller • Dynamic Distributed Power Control Devices	• System Performance Monitoring, Simulation and Prediction • Phasor Measurement Analysis • Weather Prediction and Integration • Ultra-fast Load Flow Analysis • Market System Simulation • Distribution Fault Location • High-speed Computing	• SCADA • Substation Automation • Transmission Operations, Energy Management Systems and Market Operations • Distribution Automation • Demand Response • Condition-based Maintenance • Outage Management • Asset Optimization

E. Decision Support

Despite the power systems are getting smarter and smarter they will still need constant monitoring and control by the system operators. Actually, in many cases the monitoring task will become even more challenging as alternative operation sequences for occurring contingencies will increase due to increased controllability of the system. Thereby, different Decision Support Tools such as data mining, fast simulation and advanced visualization can be estimated to become a more essential part of the system monitoring in the future. E.g. data mining can be used to process more effectively the extensive amount of measurement data provided by the system components and thereby make it easier to draw a right conclusion related to different operational contingencies. There again, fast simulation and e.g. state estimation procedures can be utilized effectively in estimating the state of the system in real time or predicting the possible operation states in the future. Advanced visualization will help the system operator to monitor e.g. the voltage and frequency levels or stability indices, such as damping level, of the system comprehensively and thereby enable fast reaction in case, when any of the indices reaches a predefined critical level. As a conclusion, Development of more advanced Decision Support tools will help the system operator in more comprehensive management of the state of the system and thereby increase the robustness and reliability of the power system with increasing amount of Smart Grid related applications.

FACTS DEVICES FOR THE HIGH VOLTAGE SMART GRIDS

Since the very first introduced FACTS applications development of the FACTS technology has been rapid and various different FACTS applications have been introduced to enable more robust and effective utilization of existing power system. Especially the fast development of power electronics has enabled designing of FACTS devices for higher voltage levels and thereby expanding the possible application area of the devices. However, depending on e.g. the connection principle of the device (shunt vs. series) and applied switching technology (thyristors, GTOs, IGBTs) each FACTS device has its own specific operational characteristics and proper selection of the applied FACTS device should always be done regarding the expected contribution of the device to the network quantities. In addition to traditional application areas of the FACTS devices development of Smart Grids will open totally new possibilities for utilization of the FACTS technology. E.g. integration of Renewable Energy Sources (RES) based electricity generation into existing networks and their effect on the energy flows of the system will set new challenges also for operation of FACTS devices. On the other hand, advanced real-time measurement of the system quantities will enable more effective utilization of the FACTS devices for the purposes of the system operator. The HVDC technology can be considered to have various similar control characteristics such as the FACTS devices and it is predicted to become one of the backbones of energy transmission concepts of the Smart Grids. [9, 10]

A. Thyristor technique based FACTS Devices

Static Var Compensator (SVC)

Static Var Compensator (SVC) is the most common and well known example of FACTS related applications. (Fig. 2) SVC unit can include either only controllable inductive branch, Thyristor Controller Reactor (TCR), or both controllable inductive and capacitive branches, namely TCR and Thyristor Switched Capacitor (TSC). In addition, filters for the lowest order harmonics are required to ensure the appropriate quality of the electricity in the connection point. Utilization of these components enables wide operation range in both inductive and capacitive regions. However, the compensation capacity of the device is directly related to the voltage level of the connection point, which decreases the effectiveness of the device in low system voltages. Also, response time of the device is characterized by the fact that thyristors can be turned off only at the time of current zero crossings, which basically leads to response times greater than one fundamental cycle.

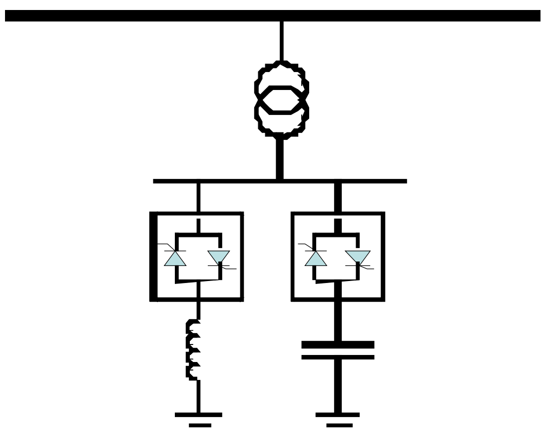


Fig. 2. Main configuration of SVC

Thyristor Controlled Series Capacitor (TCSC)

Thyristor Controlled Series Capacitor (TCSC) provides continuously variable series reactance for the transmission line, which can be applied effectively e.g. in power flow control and stability enhancement of the electrical system. (Fig. 3) The applied technique is in a way analogous for SVC with parallel connection of capacitor and TCR branches. Basically, compared to SVC, TCSC can be considered to have greater ability to enhance the transmission capacity of the system due to its series compensation characteristics. In many of the existing TCSC implementations, TCSC is combined with the traditional fixed series capacitor, which improves both cost efficiency and reliability of the implementation. Depending on the current withstand characteristics of the device it can also be utilized to decrease the fault current levels of the transmission line. In general, basic operation conditions of the device can be considered demanding due to operation in voltage level of the transmission line (usually hundreds of kVs).

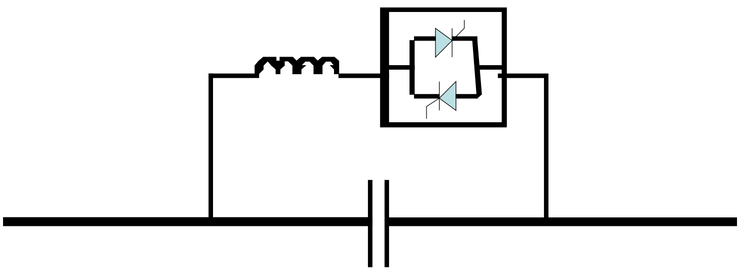


Fig. 3. Main configuration of TCSC

Thyristor Protected Series Capacitor (TPSC)

Thyristor Protected Series Capacitor (TPSC) or Short Circuit Current Limiter (SCCL) can be regarded as counterparts for the TCSC with increased fault current withstands levels. Consequently, they can be applied more effectively in controlling the fault current levels of the transmission line and thereby enabling more effective utilization of the transmission line capacity in case, where high fault current levels restrict the capacity of the system. The main configuration of the TPSC and SCCL resembles the one of TCSC and are therefore not presented in the paper.

B. Voltage Source Converter (VSC) Based FACTS Devices

Static Synchronous Compensator (STATCOM)

By applying VSC based technology Static Synchronous Compensator (STATCOM) is capable of response times of only few milliseconds, which enables rapid control of the connection point voltage and provides abilities for effective harmonic cancellation. (Fig. 4)

Contrary to SVC STATCOM is capable of injecting the nominal reactive current also in presence of low connection point voltages. Energy storage in the DC side of the converter would enable storage and injection of real power, which would expand even more the application possibilities of the device. Due to higher investment costs of STATCOM unit compared to SVC careful technical and economical assessment should be executed, when selecting the proper shunt compensation solution for the specific case.

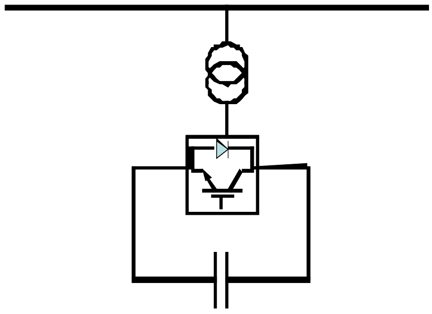


Fig. 4. Main configuration of STATCOM

Static Synchronous Series Compensator (SSSC)

Static Synchronous Series Compensator (SSSC) is more sophisticated version of the TCSC, where coupling transformer is utilized to connect the VSC terminals in series with the transmission line. (Fig. 5) Thereby, both inductive and capacitive voltage components could be injected to the transmission line. By applying energy source in the DC side of the device short term continuous reactive and real power injection to the transmission line is enabled as in case of STATCOM. However, at the moment high investment costs and complicated technical solutions limit the potential application possibilities of the device.

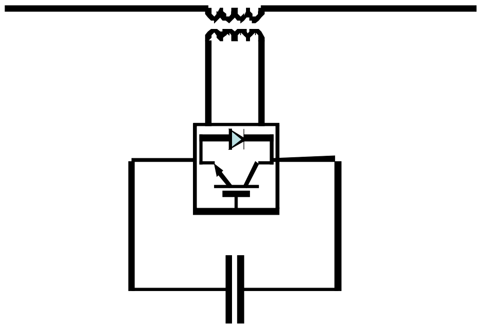


Fig. 5. Main configuration of SSSC

Unified Power Controller (UPFC)

Unified Power Controller (UPFC) can be considered as one of the most versatile FACTS devices with ability to control both real and reactive power flows of the transmission line independently within the device ratings. (Fig. 6) It is basically a combination of a SSSC and STATCOM with a common DC circuit. Moreover, SSSC and STATCOM parts of the device can also be used independently. Apart from the few prototype installations of the UPFC, high expenses and complicated technological solutions decreases the interest towards this device at the moment. However, in the future, when importance of robustness and flexible controllability of the system increases, the interest towards the UPFC is estimated to increase.

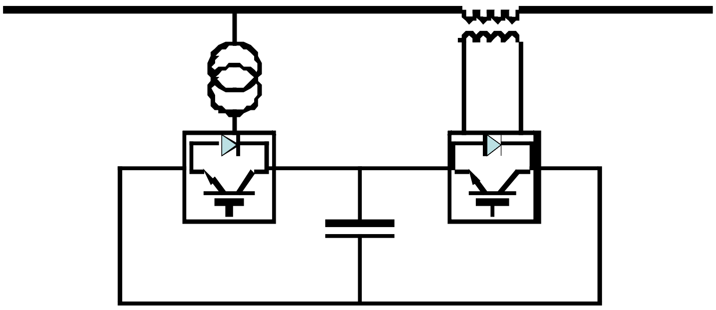


Fig. 6. Main configuration of UPFC

Interline Power Controller (IPFC)

Interline Power Controller (IPFC) resembles the UPFC configuration with an exception that the STATCOM and SSSC parts of the device are connected to separate transmission lines enabling e.g. real power balancing between the lines. (Fig. 7) Basically, due to similar technical solutions as in UPFC device IPFC cannot be seen yet as a cost-effective alternative in transmission level applications.

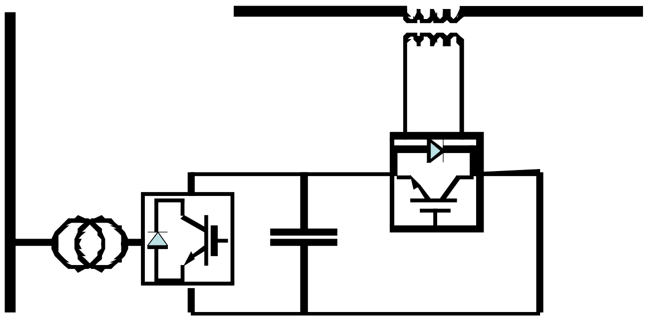
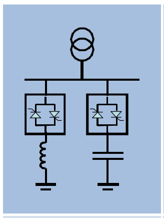
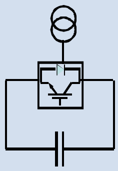
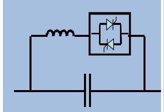
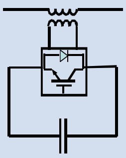
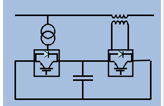
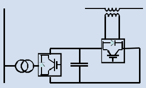


Fig. 7. Main configuration of IPFC

C. Summary of the Main Characteristics

To give more comprehensive insight to the benefits and possible application examples of the presented FACTS devices Table II presents a rough estimation of the level of contribution of the different FACTS devices on the specific dynamic phenomena of the system.

TABLE II

Device	Basic scheme	Voltage Control	Power Flow Control	Oscillation Damping	Fault Current Limiting
SVC (Static Var Compensator)		●●●	●	●●●	●
STATCOM (Static Synchronous Compensator)		●●●	●	●●●	●
TCSC (Thyristor Controlled Series Capacitor)		●	●●	●●●	●●
SSSC (Static Synchronous Series Compensator)		●●	●●	●●●	●●
UPFC (Unified Power Flow Controller)		●●●	●●●	●●●	●●
IPFC (Interline Power Flow Controller)		●●●	●●●	●●●	●●

Level of Contribution: ●●● = Significant
●● = Average
● = Small

It should be noted that in addition to inherent characteristics of the devices also the ratings and placement of the device can affect significantly the actual contribution level of the device. Therefore, comprehensive feasibility study should always be executed, when considering applying any of the presented FACTS devices in practice.

EXAMPLES OF APPLICATIONS OF FACTS DEVICES IN SMART HIGH VOLTAGE POWER SYSTEMS

A. More Effective Utilization of the Existing System Capacity

The most obvious application example of FACTS devices is utilization of them to increase system stability and thereby enable more effective utilization of the existing system capacity. Voltage support is probably the most common application example of shunt connected FACTS devices such as SVC or STATCOM. In general, maintaining the system voltages in appropriate level decreases the losses in the power transmission and enables more effective utilization of the transmission capacity. On contrary, series FACTS devices such as TCSC can increase the transmission capacity of the line directly with its series compensation capability. In addition, significant dynamic stability enhancement can be achieved by equipping applied FACTS device with additional oscillation damping controller, which decreases the risk for instability due to insufficient damping of the system.

In general, transmission capacity of the system is commonly limited more by the operation state dependent stability constraints than the actual thermal limits of the components. In this case, capacity of the power system could be utilized more effectively by improving the dynamic stability of the system. (Fig. 8) Among other approaches, FACTS devices offer an effective means to improve the overall stability and thereby increase the available capacity of the system in a cost-effective manner. For instance, studies and practical experiences of the increased transmission capacity by applying FACTS devices in Nordic and Finnish power systems are reported in [11, 12].

Moreover, in case where thermal limits become the limiting factor for the system capacity in the form of high fault current levels, FACTS applications, such as TPSC or SCCL, could be applied to relieve the system stresses in fault situations. Thereby, by applying these devices system can withstand more serious fault cases without overloading of the system components.

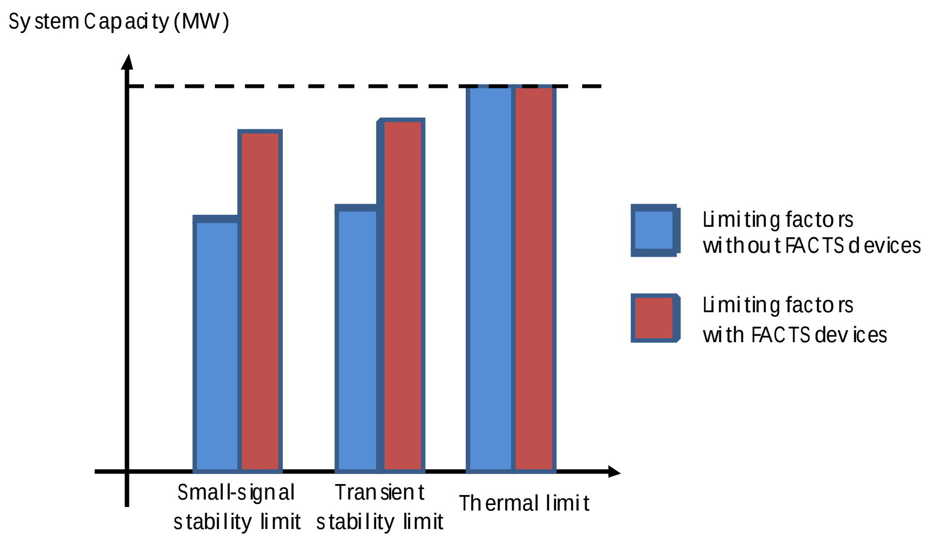


Fig. 8. Effect of FACTS devices on stability constraints of the system

B. Increasing the Energy Efficiency of Transmission Systems

In general, energy efficiency has become one of the dominating factors in making the decision of new transmission system investments. For instance, especially in transmission level systems, high voltage direct current (HVDC) will increase the energy efficiency of the electricity transmission over long distances and is therefore estimated to be applied more widely in the future. Similarly, FACTS devices offer various means to increase the energy efficiency of the electricity transmission in indirect manner. This is accomplished e.g. by providing active reactive power reserves and thereby maintaining the voltage levels of the system at optimal level or preventing loop flows in the system with active power flow management.

C. Ensuring Grid Compliance of Renewable Energy Sources

Renewable Energy Source based electrical energy generation is estimated to be in a significant role in both, replacing part of the existing, less environmental friendly, electricity generation capacity and partly covering the estimated increase in electricity demand in the future. However, often distributed nature of the renewable energy source based electricity generation and variability in available generation capacity for example in wind and solar based generation methods will set totally new challenges for the transmission system operators in ensuring e.g. the stability of the system and adequacy of electrical energy. One of the main principles to confront these challenges is to set similar interconnection requirements for these renewable energy based generation units, which concerns the traditional generation units at the moment. Herein, FACTS technology can offer various benefits in ensuring the grid compliance of the renewable energy source based electricity generation.

As an example of utilizing FACTS technology in connection of renewable energy sources is ensuring the grid compliance of the offshore wind farm with active compensation device. (Fig. 9) FACTS devices such as SVC or STATCOM will enable effective reactive power compensation in both steady state and transient situations. In addition, combining energy source with STATCOM will enable temporary storing of the electrical energy and thereby smoothing down the variability in the generation profile. [13]

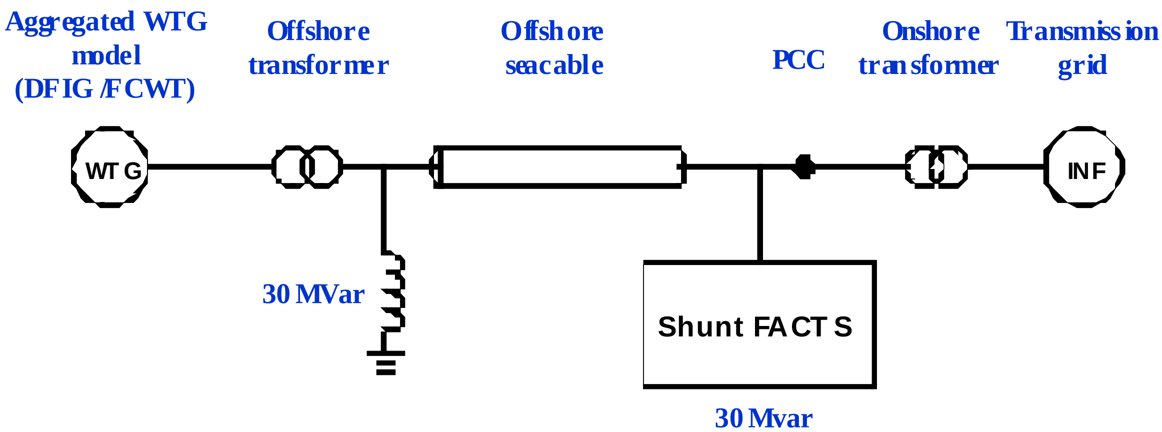


Fig. 9. Enhancing grid integration of offshore wind farm by means of shunt FACTS device

D. WAMS, WACS & FACTS

Presently, control of the FACTS devices is based mainly on local measurement signals and reference values. However, synchrophasor measurement technique and its applications, such as Wide Area Measurement Systems (WAMS) and Wide Area Control Systems (WACS) will offer new possibilities for controlling the installed FACTS devices in more effective manner. For instance this could mean taking into account the state of the system as a whole and setting the reference values of the controllers to enhance the stability of the system rather than concentrating only to the state of the system in the connection point of the applied controller. This wide-area management of the controllers will enable more effective utilization of the controlling capacity of the FACTS devices and enhance the stability of the system in more advanced manner.

However, due to the complexity of the power system, optimizing the state of the system and its controllers will obviously require sophisticated analysis techniques and careful assessment to ensure simultaneously the appropriate level of reliability in the process.

Presently, despite the numerous installed synchrophasor measurement units worldwide, complete systems utilizing synchrophasor based management of the controllable components of the system are still rather rare. Therefore, significant potential to increase the controllability of the transmission level power systems will become available when the individual measurement units are integrated into single measurement system and applied in the online management of the controllable devices of the system.

CONCLUSIONS

Despite the term Smart Grids refers basically to all smart and intelligent applications of modern power systems the applied solutions can vary significantly between transmission and distribution level systems. In general, whereas the Smart Grids in distribution system level can be considered rather well characterized and discussed in various forums the basic concepts of transmission level Smart Grids are discussed less frequently. Thereby, this paper overviews briefly some of the transmission system related elements of Smart Grids with special attention to FACTS devices and their application examples. It is also emphasizes that, in the future, smarter distribution and transmission level systems will have more interaction with each other and the possible common applications will enhance the operation of both systems.

The paper refers to reference [4] when dividing the key elements of transmission level smart grids into five separate technology areas, which together are considered to constitute the main characteristics of the transmission level smart grids. After listing the key elements of transmission level Smart Grids role of FACTS devices in enabling many of the Smart Grids related functionalities for the existing high voltage power systems are discussed briefly. It can be concluded that FACTS devices and their various applications can be assumed to have significant role in enhancing the intelligence and robustness of the existing power systems.

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13. Subtransmission high voltage Smart Grids

Author: Juhani Bastman

DEFINITION OF SUB-TRANSMISSION

For the overall function of transporting electrical power from the location where it is pro-duced to the location where it is consumed, two types of networks can be distinguished.

- The transmission networks transferring in bulk the electricity from generating sta-tions to areas of consumption
- The distribution networks transferring the electricity to consumers within an area of consumption

Transmission networks can be interconnected by means of one or more links, and certain elements of a given network can be categorized as having an interconnection function.

The boundary between transmission and distribution networks is often not clear. It depends on the geographical situation or the ownership or even the changing power needs of a region. The network division mentioned above, although it is not always clear, is simple to apply in practice. In many countries a more fine division is used. The term sub-transmission (network) is in common use. According to the standard IEC 60038 [2] the sub-transmission voltage rating is defined as

- High voltage (HV): for a phase-to-phase voltage between 35 kV and 230 kV, the standard ratings are: 45 kV - 66 kV - 110 kV - 132 kV - 150 kV - 220 kV.

The function of the sub-transmission can be described as follows: sub-transmission forms an intermediary between (bulk) transmission and (MV) distribution in order to be able to trans-fer and spread out the electrical power efficiently and economically for those cases where the distribution networks are not connected directly to the transmission network. One elec-tricity network structure is presented in figure 1, which presents the structure of the French system [3].

Quite often transmission networks do fulfil an interconnection function, sub-transmission networks will rarely have that function. On the other hand sub-transmission networks can play an important role in distribution while transmission networks normally do not have a distribution function. This means that a network with a primary sub-transmission function can also support the transmission in certain situations or equally support the distribution networks. During it’s life-time the function of the network parts can change. In most of the existing systems the transmission networks became sub-transmission networks when higher voltage levels were introduced for the transmission function.

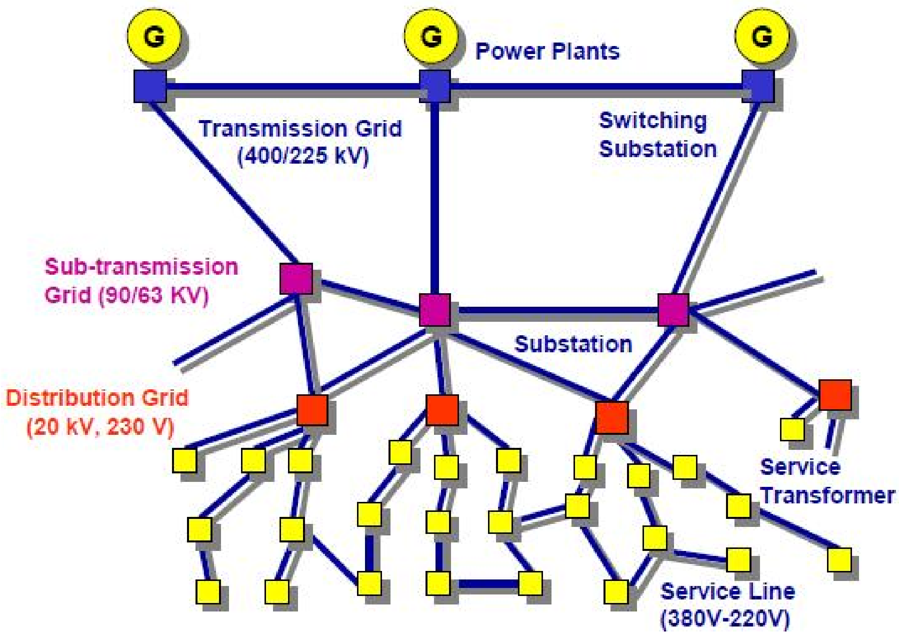

Figure 1. The structure of the power system in France.

The Finnish system

In Finland the transmission voltages are the 400 kV and the old 220 kV which in fact, ac-cording to the standard, belong to the sub-transmission network. On the other hand the pre-sent division is also based on network ownership and that criterion defines 220 kV network as a part of the transmission network.

Nowadays the Finnish term Alueverkko means:

- Those parts of the 110 kV network that are not part of the transmission grid (owned by Fingrid)
- All 45 – 110 kV networks owned by distribution companies

The definition varies in different parts of the country which is not desirable. Another thing to remember is that in the capital area of Helsinki, there is a need to move even up to 400 kV voltage level inside the city. The categorization of this type of network is quite unclear according to the used definition. Figure 2 presents those distribution companies which own the most of the 110 kV network excluding Fingrid.

Normally, the sub-transmission networks are organised in a loop to reinforce the security of the system. In the Finnish sub-transmission network the most of the 110 kV network is ra-dial and only 110 kV sub-transmission networks in the big cities are meshed and also oper-ated meshed. The structure of these sub-transmission networks is generally of overhead-lines (sometimes underground cables near urban areas). The protection systems are of the same kind as those used for transmission networks and the control is regional [3].

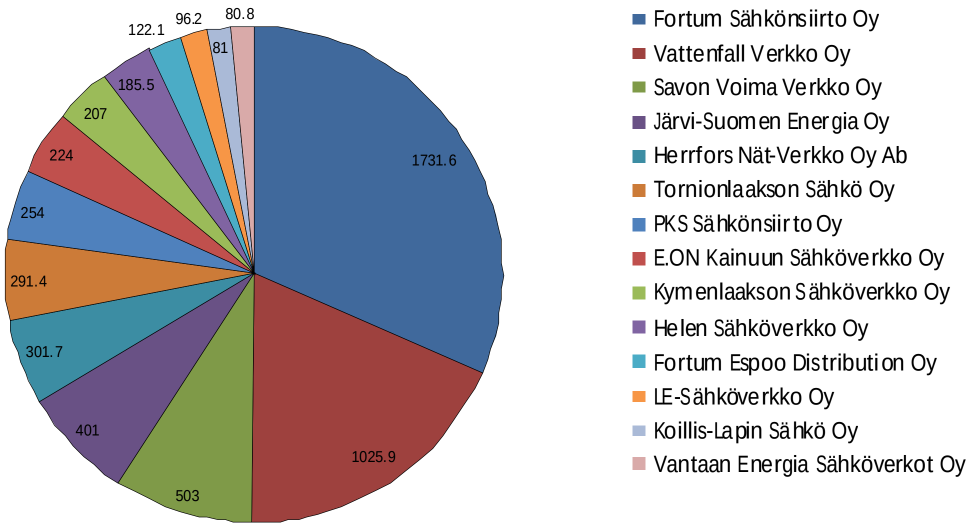

Figure 2. The biggest (line length) owners of the 110 kV network.

It should be bear in mind that 110 kV network owned by Fingrid is not included in the Fin-nish sub-transmission network (called Alueverkko). The definitions are currently under focus because of the new EU directive. The Directive of Internal Market for Electricity (Sähkön sisämarkkinadirektiivi (EU)) was given on July 2009. The directive is to be enforced in the national legislation not later than March 2011. The main modification to the present law is essentially on the fact that power transmission companies are not allowed to own in the future power producers or vice-versa. In Finland the Ministry of Trade has established a working group to settle the matter.

SMART GRID IN TRANSMISSION/SUB-TRANSMISSION LEVEL

System monitoring and control [3]

Energy Management system (EMS) is needed to operate and control the network in real time. It includes communication facilities to capture the current state of the system and to instruct generating plants and other controllable system components. Figure 3 shows the four levels form in the hierarchy of a power system with EMS:

- Level 0: network and substations; this cover switchgears, interconnections, service lines, service transformers, etc.
- Level 1: local controls or substations; these include protection relays, tap-change controllers and compensator controls with operating channels to level 0 units. Level 1 controls often comprise digital/electronic devices for voltage and current meas-urements, interlocking and facilities for receiving and sending data up to the next level.
- Level 2: area controls; man-machine interfacing at this level enables both control and maintenance; so the whole system can be kept in reliable and efficient condition.

- Level 3: Supervisory Control and Data Acquisition (SCADA). It is a single control centre that accepts data from the various level 1 collectors and displays it in a mean-ingful way to the control operators. With powerful computer processing, the SCADA feeds into an Alarm Management subsystem to supplement automatic relay operation and to give warning about any system abnormality that cannot be detected at levels 1 or 2.

The data measurements and device positions are collected in the control centre in short time intervals (from 5-10-15 seconds to 1 minute) by on-line digital processors. SCADA data includes real-time data from switchgear, isolators and other connectors. The EMS processes these data on-line and, using mathematical methods and voltage measurements at pre-selected network positions, it determines the state of the system. Such a process is called “state estimation” and enables the control of the system. The incoming data must be checked for further utilisation: contingency checking, economic scheduling, automatic fre-quency control, etc.

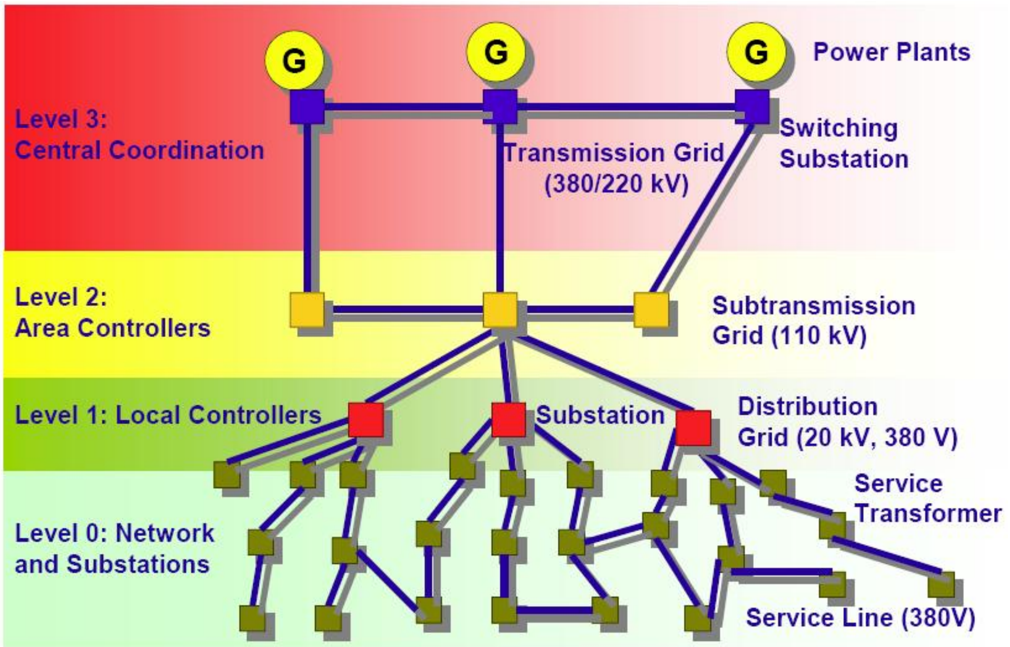

Figure 3. Hierarchy of controls required for an Energy Management System (EMS).

Use of smart grid technologies for system enhancement and grid inter-connection

The following technologies for the active control of the active or reactive power flow or voltage are widely used in the transmission networks. However these same technologies will be applied in the sub-transmission area as well. The main counter force at present is still the high costs.

One new idea is the concept of a distributed approach for realizing FACTS devices, in par-ticular series FACTS devices. The increasing performance and decreasing price of electron-ics, power electronics and communications technologies have transformed entire industry sectors. It is proposed that a similar approach to the implementation of high power FACTS devices can provide a higher performance and lower cost method for enhancing T&D sys-tem reliability and controllability, improving asset utilization and end-user power quality, while minimizing system cost and environmental impact [7].

With the increasing deployment from Distributed Generation, in particular Renewable En-ergies, distribution networks in their current design will not stand the new constraints while satisfying to the requirements in supply quality. Since networks cannot be reinforced at fast pace, the solution resides in a SmartGrid automation to balance dynamically consumption and generation within the capacity limits from distribution grid, both at local and global scales. The management from distribution networks will evolve from a passive into an active manner, as for transmission and sub-transmission networks [5].

HVDC-technology [4]

During the development of HVDC, different kinds of applications were carried out. They are shown schematically in Fig. 4. The first commercial applications were HVDC sea cable transmissions, because AC cable transmission over more than 80-120 km is technically not feasible due to reactive power limitations. Then, long distance HVDC transmissions with overhead lines were built as they are more economical than transmissions with AC lines. To interconnect systems operating at different frequencies, Back-to-Back (B2B) schemes were applied. B2B converters can also be connected to long AC lines (Fig. 4a). A further applica-tion of HVDC transmission which is very important for the future is it’s integration into the complex interconnected AC system (Fig. 4c). The reasons for these hybrid solutions are ba-sically lower transmission costs as well as the possibility of bypassing heavily loaded AC systems [4].

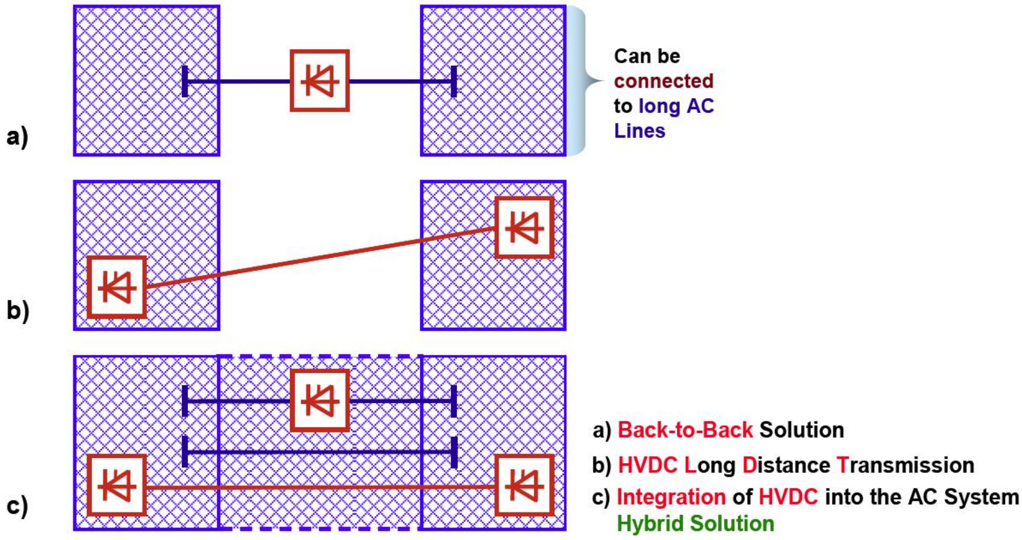

Figure 4. Types of HVDC transmissions.

Typical configurations of HVDC are depicted in Fig. 5. The major benefit of the HVDC, both B2B and LDT, is its incorporated ability of fault-current blocking which serves as an automatic firewall for blackout prevention in case of cascading events, which is not possible with synchronous AC links.

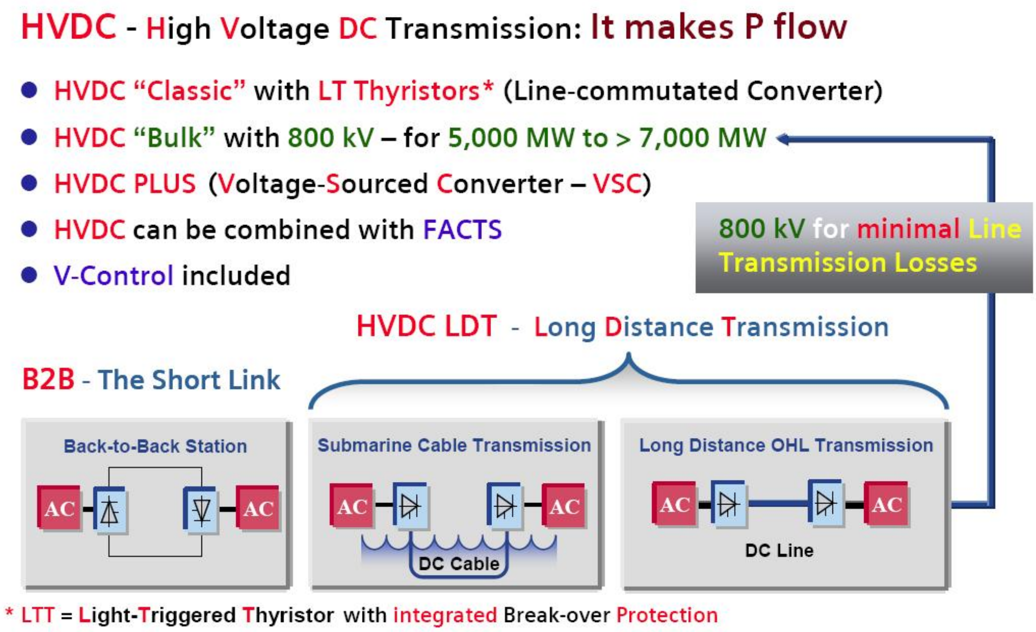

Figure 5. HVDC configurations and technologies.

HVDC PLUS-technology [4]

HVDC PLUS (Fig. 6) is the preferred technology for interconnection of islanded grids to the power system, such as off-shore wind farms. This technology provides the "Black-Start" feature by means of self-commutated voltage-sourced converters (VSC). Voltage-sourced converters do not need a "driving" system voltage; they can build up a 3-phase AC voltage via the DC voltage at the cable end, supplied from the converter at the main grid. Siemens uses an innovative Modular Multilevel Converter (MMC) technology for HVDC PLUS with low switching frequencies. Therefore only small or even nor filters are required at the AC side of the converter transformers. Fig. 6 summarizes the advantages in a comprehensive way.

HVDC-light [6]

HVDC Light is a fundamentally new power transmission technology developed by ABB. It is particularly suitable for small-scale power generation/transmission applications and ex-tends the economical power range of HVDC transmission down to just a few tens of mega-watts (MW).

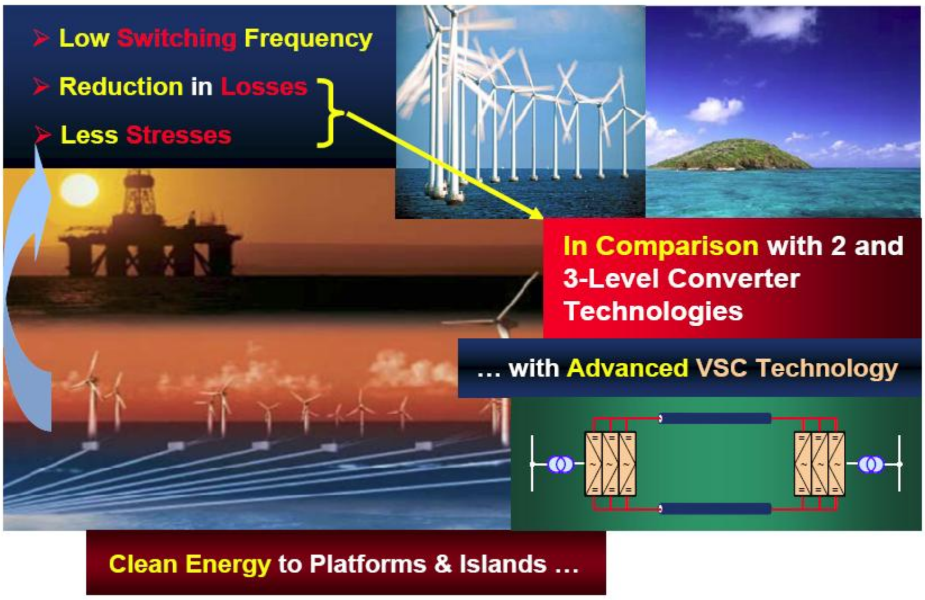

Figure 6. HVDC with VSC – HVDC, the power link universal system.

The HVDC Light system comprises two (or more) converter stations at the ends of a trans-mission line. Although conventional DC overhead lines could be used for the link, maximum benefits would be derived from the system when underground cable is used as the link between the two converter stations. In many cases the evaluated cable cost is lower than for an overhead line, and the environmental and other permits for a HVDC Light cable are much easier to obtain. Besides, being a cost competitive alternative to conventional AC and local generation, HVDC Light also opens up new possibilities for improving the quality of supply in AC power networks. With an HVDC system, the power flow can be controlled rapidly and accurately as to both the power level and the direction. HVDC also provides isolation from disturbances that occur within the connected AC networks. The technology was introduced in 1997. A number of transmissions up to 330 MW are in commercial operation and more are being built.

FACTS-technology [4]

FACTS, based on power electronics, have been developed to improve the performance of weak AC Systems and to make long distance AC transmission feasible. FACTS can also help solve technical problems in the interconnected power systems. FACTS are applicable in parallel connection (SVC, Static VAR Compensator - STATCOM, Static Synchronous Compensator), in series connection (FSC, Fixed Series Compensation – TCSC/TPSC, Thy-ristor Controlled/Protected Series Compensation - S'C, Solid-State Series Compensator), or in combination of both (UPFC, Unified Power Flow Controller - CSC, Convertible Static Compensator) to control load flow and to improve dynamic conditions. Fig. 7 shows the basic configuration of FACTS.

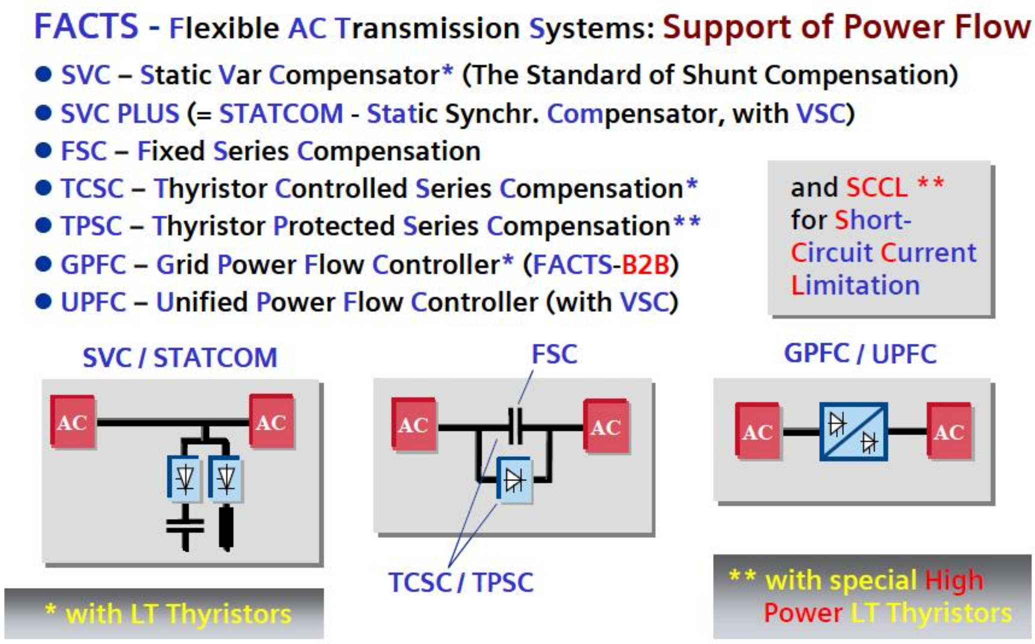

Figure 7. Transmission solutions with FACTS.

Transmission/Sub-transmission difference

To gather above technologies and their applications together we can form the following catalogue:

Transmission System (275kV, 330kV, 400kV, 500kV, 765 kV)

- High level of monitoring and control
- Incorporates technology for power flow management
- Technology improvements (FACTS) & Grid Interconnection
- HVDC-technology widely used
- Wide area control
- Phase measurement units

Sub-transmission System (110kV, 130kV)

- Reasonably high level of monitoring and control
- Incorporates some technology for power flow management
- Technology improvements (FACTS) & Energy Storage
- HVDC-technology not routinely used

- HVDC light as alternative
- The centralized wind farms connected usually to sub-transmission grid
- Phase measurement units

CONCLUSION

The smart grid of the future is generally characterized by more sensors, more communication, more computation, and more control. The component technologies are all known but putting them together into a coherent whole and transitioning from the present technologies to the new, is a significant (and expensive) undertaking. The technical feasibility, however, is not in doubt, and the cost of not undertaking this journey is significantly higher than the in-vestment needed [8].

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14. Smart substation

Author: Ari Nikander

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.

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

- o 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.
    - o switching off the whole protection system and causing interruptions in supply
    - o 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
    - o 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.
    - o 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.

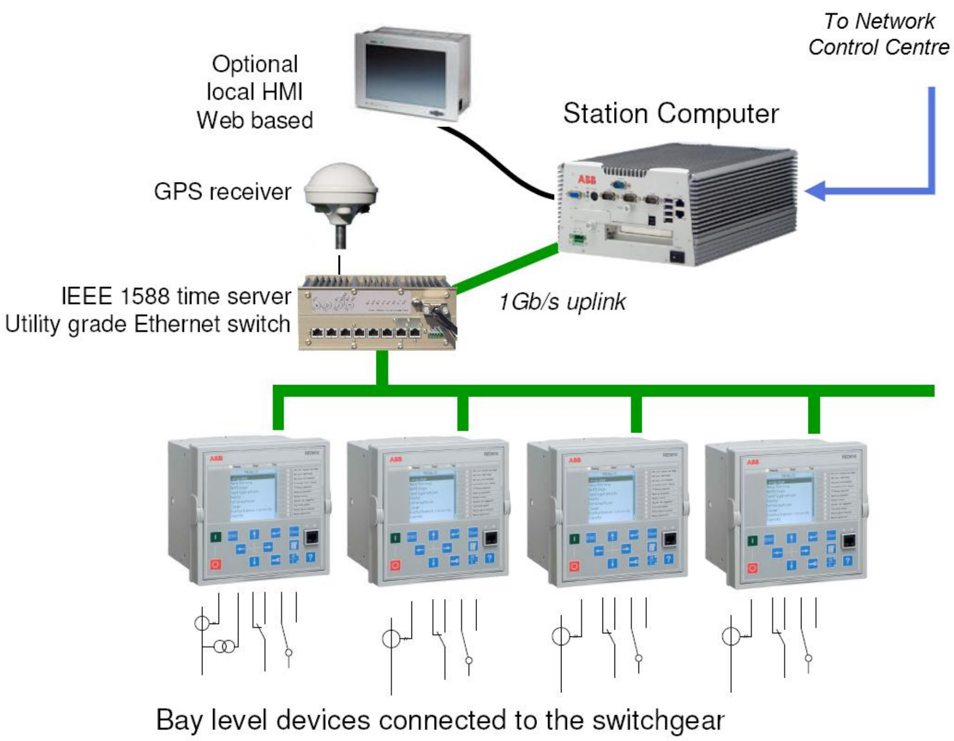

Figure 1. New setup with a central Station Computer [Val09].

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.

STATION LEVEL FUNCTIONALITY IN FUTURE SMART SUBSTATIONS [VAL10]

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.

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
    - o Advanced directional earth fault protection
    - o Advanced directional overcurrent protection
    - o Bus bar protection based on blockings
- Control operations based on blockings
    - o 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)
  - o 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

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

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.)

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.

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

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

- o Standard communication products
- Totally integrated software based functions
- IEC 61850 as design base

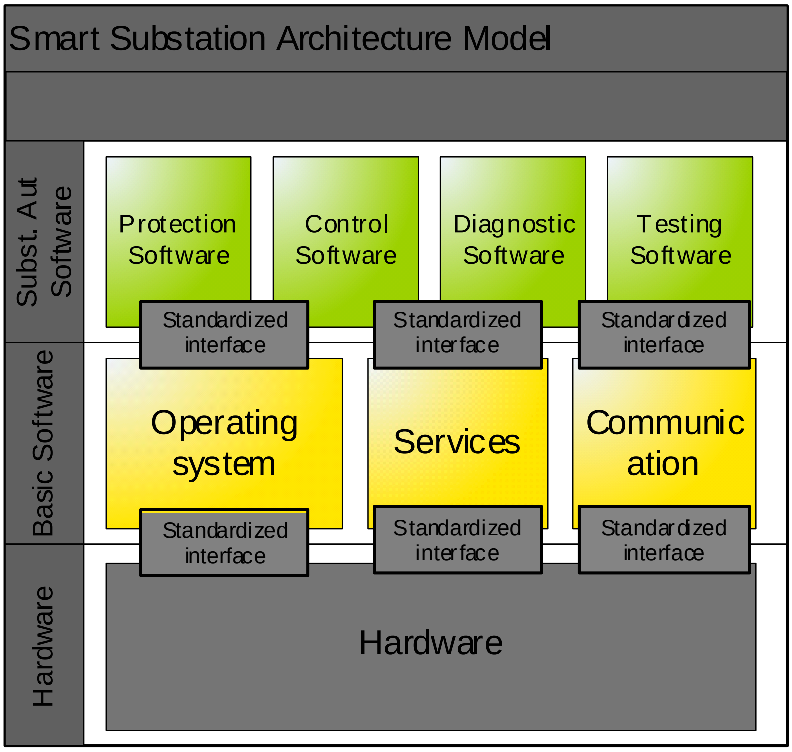

Figure 2. New substation concept [Car10].

Concerning to substation automation software Reference [Car10] highlights

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

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”.

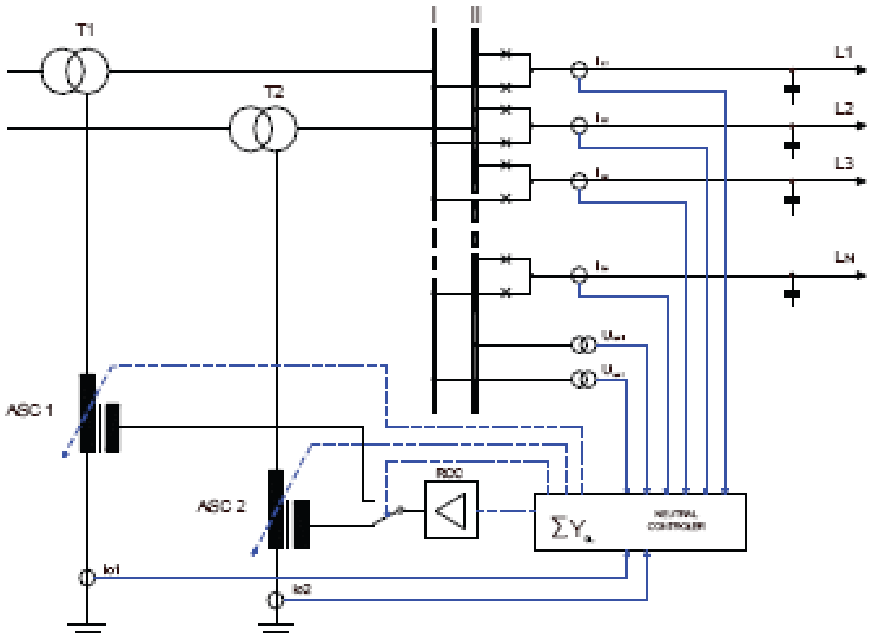

Figure 3. RCC Ground Fault Neutralizer for twin bus bar, block diagram.

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

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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15. Condition monitoring in Smart Grids

Author: Pertti Pakonen

INTRODUCTION

The term Smart Grid refers to a modernization of the electricity delivery system so it monitors, protects and automatically optimizes the operation of its interconnected elements. The Smart Grid is characterized by a two way flow of electricity and information to create an automated widely distributed energy delivery network. The Smart Grid will improve power reliability, power quality and energy efficiency [Nis09a].

The Smart Grid provides a perfect platform for developing new condition monitoring technology and applications. The concept of condition monitoring covers a wide field of different condition monitoring methods applied to various power apparatus [Han03a]. This presentation focuses mainly on partial discharge (PD) measurements, which is a condition monitoring method widely applicable to different power apparatus. The method is based on. The emphasis in this presentation is on its application to condition monitoring of underground cables. PD based condition monitoring has been studied for more than half a century, but especially during the past two or three decades it has gained importance and found new commercial applications. This is, on one hand, due to the evolution of digital measurement technology and computer technology who have increased the possibilities of this technique by enabling automatic condition monitoring applications. On the other hand, for example, old paper-oil insulated underground cable networks are coming to an age, where the fault rate begins to increase. Additionally, many novel HV products such as polymeric cables and gas insulated switchgear, withstand only very little or not at all partial discharges (and on the other hand PD signal propagates well in them), which makes PD measurement a feasible condition monitoring method for these products. This has opened new areas of application for PD based condition monitoring in addition to the old ones. However, the cost of measuring equipment and data communication (when built only for the purposes of condition monitoring) has still been too high to enable a wider implementation of these techniques in electricity distribution networks. Thus, the condition monitoring applications implemented so far have been mainly in transmission networks and industrial networks in which the costs of unpredicted interruptions are highest [Ren09a]. This applies to practically all condition monitoring methods, not only PD measurements. In distribution networks (0.4…45 kV) the maintenance of power apparatus has been mainly time-based.

SMART GRID FROM THE VIEWPOINT OF CONDITION MONITORING

Condition monitoring, condition based maintenance and proactive detection, location and repair of incipient faults seems to be missing or lacking concrete plans in many smart grid research programs [Nis09a]. However, to achieve the contradictory goals of reliability and cost-effectiveness in Smart Grids it is necessary to move over from time based maintenance to reliability centered maintenance (RCM) and eventually condition based maintenance (CBM) not only in the transmission networks but also in the low voltage (LV) and medium voltage (MV) distribution networks. This way unnecessary maintenance can be kept to a minimum and the maintenance may be coordinated considering the criticality of the component in achieving a high system reliability.

The Smart Grid offers several characteristics which facilitate the implementation of condition monitoring:

- intelligent electronic devices (IEDs) with (or into) which PD measurement functions could be integrated
- two way data communication between IEDs or between IEDs and information systems, which enables:
    - traditional “upstream” data transfer (maybe with a higher capacity than earlier) from measuring units to centralized information systems (for example, centralized data storage and analysis system or control room)
        - measurement data (condition monitoring quantities, load, temperature etc.
    - “downstream” data transfer from centralized information systems (for example, distribution management system, DMS) to measuring units
        - network data, network configuration data, load data, etc.

The existence of IEDs with good communication facilities distributed around the power network enables real-time measurements and monitoring of different quantities even at distribution voltage levels. The evolution of digital data acquisition already enables even high frequency measurements necessary, for example, in PD measurements, disturbance recording and fault location at a relatively low cost.

CHARACTERISTICS OF FINNISH DISTRIBUTION NETWORKS

Finnish distribution networks are characterized by a relatively small length of underground cable network. In 2009, only approximately 11 % (14 865 km) of Finnish MV networks were constructed using underground cables. Although the percentage of underground cables in Finnish MV networks is increasing it still is very low compared to other Scandinavian countries (Sweden, Norway and Denmark) and especially many densely populated central European countries such as Netherlands and Belgium. During the past few years the interest towards MV underground cabling has increased in rural networks as well, mainly due to long interruptions by exceptional weather phenomena and involving large numbers of customers.

Table 1. Overview of the existing underground cables in a few European countries [Ano04a, Ano03b, Ano10a].

Low, medium and high voltages

Voltage	60-150 kV			MV			LV		
km	Overhead	Under ground	Under ground [%]	Overhead	Under ground	Under ground [%]	Overhead	Under ground	Under ground [%]
Netherlands	6011	3655	38	0	101900	100	350	145000	100
Belgium	4777	395	8	9750	55250	85	60480	47520	44
Germany	71609	4740	6	190000	285000	60	231500	694000	75
UK	21836	3789	15	204600	167400	45	71360	305370	81
Denmark	10256	1902	16	32450	22550	41	32200	59800	65
Austria				34200	22800	40	55250	9750	15
Sweden	15000			93440	52560	36			
Italy	36228	449	1	215801	115380	35	498960	210327	30
France	50111	1896	4	393190	180810	32	463888	168112	27
Norway	19001	624	3	63480	28520	31	114700	70300	38
Spain	37639	559	1	96448	26025	21	241102	40141	14
Portugal	8953	358	4	48720	9280	16	90720	21280	19
Finland 2009				119653	14865	11	143216	77291	35
Finland 2003				120650	12634	9			

In Finland, electricity distribution companies started to use polymeric cables rather late so that the 1st and 2nd generation underground cables lacking radial water protection were not installed. Thus, water tree problems have been negligible in Finnish underground cable networks. This may be one reason for the lower fault rates of Finnish underground cable networks compared to many other European countries. Finnish MV networks are also characterized by long feeders and sometimes difficult terrain, both of which have probably contributed to the low percentage of underground cables.

STATE OF THE ART IN CONDITION MONITORING

Many condition monitoring techniques for power apparatus are already commercially available, but they are not widely applied. Especially, in distribution networks, condition monitoring is still quite rarely applied. There are several reasons for this:

- the price of condition monitoring (CM) including the acquisition and operating costs may be high compared to the expected financial benefits gained by CM
- standardization is inadequate or it is missing so that the customer (e.g. network company) is tied to the often closed system of one vendor

Nevertheless, for example in Finland, the following condition monitoring methods, services or applications are already in use:

- off-line
  - PD and tan-delta measurements of underground cables (the commercial service provider is Dekra Industrial Oy, earlier Polartest)
- periodic on-line
  - PD monitoring of large generators and motors (Fortum Service Oy [Nur05a])
  - dissolved gas analysis of power transformers (Fingrid Oyj)
  - inspection of poles and overhead lines (Fingrid Oyj, distribution network companies)
  - thermal imaging of substations and transformer stations (Fingrid Oyj, distribution network companies)
- continuous on-line
  - condition monitoring of breaker operation is integrated in new feeder terminals

This chapter focuses on condition monitoring based on PD measurement and especially on its applications in condition monitoring of underground cables.

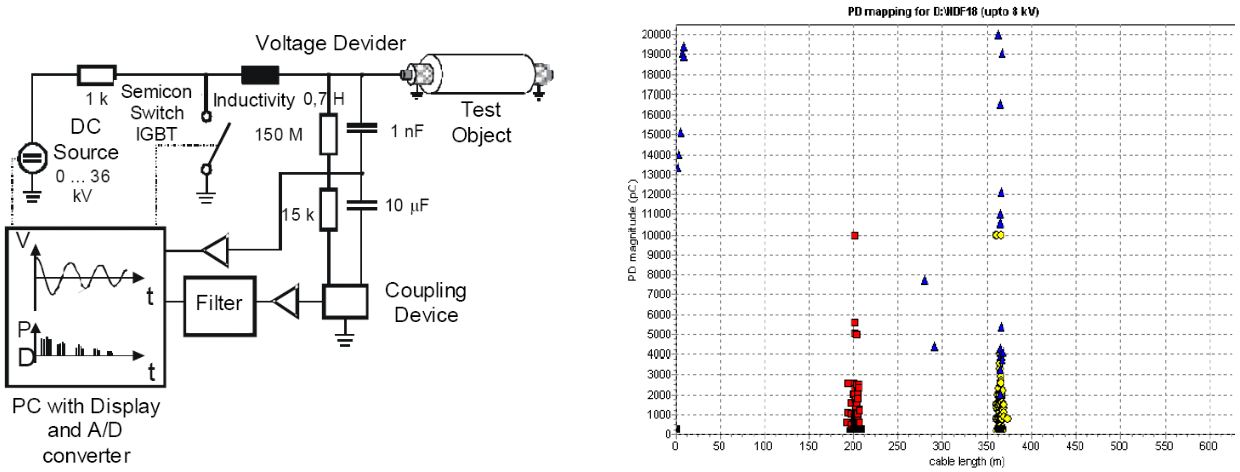
EXAMPLES OF COMMERCIALLY AVAILABLE CONDITION MONITORING SYSTEMS

Commercially available condition monitoring systems may be divided into off-line, periodic on-line and continuous on-line systems. Off-line measurements [Mas06a, Col01a] are characterized by

- a possibility to use voltage different from normal operating conditions
- a possibility to use frequency different from normal operating conditions
- less interference than in on-line measurements
- rapidly developing faults are likely to remain undetected

A well known and relatively widely used off-line condition monitoring system is the so called oscillating wave test system (OWTS), which is nowadays marketed by SebaKMT [Ano07a]. The system is capable of performing PD detection and location in cables and also tan-delta measurement can be performed with the same system. Figure 1 a) presents the basic principle of the OWTS. The cable capacitance id charged with an increasing DC voltage and then discharged through an inductance (forming a LC series resonance circuit). Thus, a damping sinusoidally oscillating voltage occurs across the cable insulation enabling PD detection, location and measurement of PD extinction voltage with a single measurement. Figure 1 b) presents the PD location chart, where the two groups of dots indicate PD activity in two joints of the measured cable.

Figure 1. a) Basic principle of OWTS, b) PD location chart [Pet04a].



Periodic condition monitoring [Ren09a] on live network (on-line measurements) are characterized by the facts that it:

- does not disturb the normal operation of the network
- enables measurements in different load conditions
- variation of test voltage and frequency is not possible
- somewhat higher interference level and more difficult fault location than in off-line measurements
- possibility to use more accurate and expensive instruments than in continuous on-line measurement

Examples of commercially available periodic on-line CM systems are PD Surveyor and PD Longshot both produced by HVPD Ltd. From UK. The former is designed for quick PD detection in e.g. switchgear and cables and the latter is also capable of locating the PD source. Both can utilize different sensors: current transformer, transient earth voltage sensor and ultrasonic sensor.

Continuous on-line measurements

- rapidly developing faults can be detected, as well
- covers all load (and other operation) conditions and stresses
- measurement and analysis of measured data is automatic
- most suitable for utilizing Smart Grid infrastructure (IEDs, communication and information systems)

An example of continuous on-line PD monitoring system is the HVPD Multi permanent PD monitoring system [Ano09a] and ASM On-line partial discharge monitor (Fig. 2) by IPEC Ltd [Smi09a].

In addition to HVPD Ltd. periodic and continuous on-line PD monitoring systems are produced also by IPEC Engineering Ltd., Lemke, Adwel and Omicron.

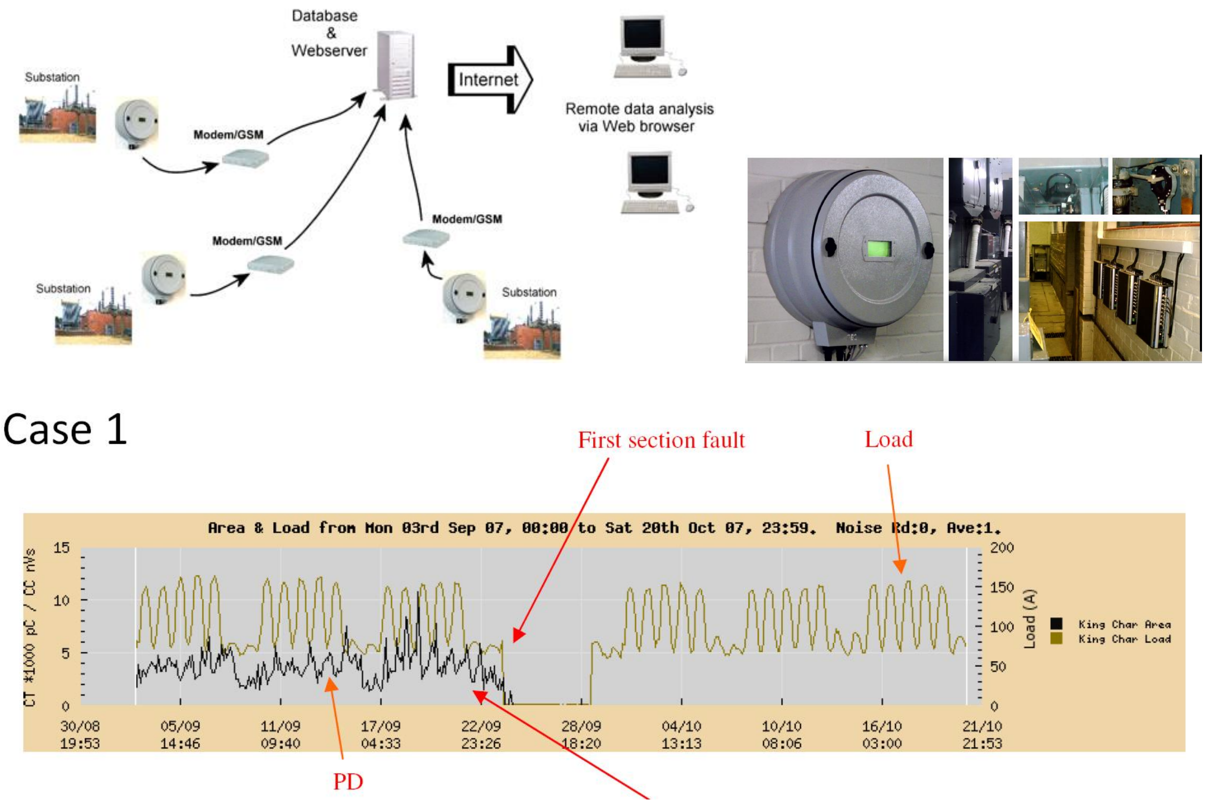


Figure 2. ASM On-line partial discharge monitoring system and a diagram showing the trend recording of load and PD intensity of one MV feeder.

CONDITION MONITORING APPLICATIONS IN EVERYDAY USE

The most well known on-line partial discharge monitoring system is used by EDF Energy, which provides electricity to London, eastern and southeastern England. EDF Energys's 11 kV and 6.6 kV underground cable network length is 38 000 km and its replacement cost is £ 4 billion. More than 600 of the 11 kV feeders are monitored for PD on-line. The reason for this is that the financial and environmental cost of replacing all the older cables are prohibitive, so the utility is seeking to establish maintenance and replacement strategies that will avoid premature replacement and reduce unplanned outages. On-line PD monitoring has proved to be an efficient way of ranking the cables so that the ones in poorest condition will be replaced first [Mic07a].

Other condition monitoring methods used by EDF energy [Gar08a]:

- power transformers: moisture and hydrogen monitoring, on-line DGA (dissolved gas analysis), Hydran 2-device
- substations/switchgear: thermal imaging, periodic on-line PD
- overhead lines: HD photography

ACTIVE RESEARCH AREAS IN CONDITION MONITORING

The following research areas in condition monitoring have been very active during the recent years:

- Periodic and continuous on-line PD measurement, applications:
    - underground cables (detection and location of different defects and incipient faults) [Ren09a]
    - transformers [Sin08a, Zhe09a]
- Novel areas:
    - Frequency response analysis (FRA) [Dub06a]
    - transformers (detection of mechanical problems and deformations in windings)
    - underground cables (detection of moisture in the cable insulation)
- Wireless sensor networks (WSN) [Ham09a, Gun10a]
- Condition monitoring of
    - motors and their mechanical loads (integrated into the frequency converter) [Aho08a, Aho09a]
    - wind turbines [Yan10a, Lu09a]

FUTURE CHALLENGES

One of the main future challenges related to condition monitoring in Smart Grids is to develop low-cost and easy-to-install condition monitoring systems which are applicable to both new and old systems and apparatus. To accomplish this standard, generic sensor solutions are needed and in general, apparatus specific solutions and excessive engineering should be avoided so that the costs of the systems can be kept low. Additionally, the acquisition, interpretation and utilization of the condition monitoring data should be flexible and as automatic as possible. On possibility could be to aim towards a continuous on-line measurement system based on a low-cost and intelligent measuring unit which would be capable of e.g. disturbance analysis and power quality monitoring, as well. The two-way communication and AMI of Smart Grids opens new possibilities to condition monitoring applications and the utilization of these technologies is one of the challenges of condition monitoring research in the future. To facilitate the integration of different condition monitoring devices and systems the standardization of interfaces should be developed. This includes both the sensor-instrument interface and the instrument-information system interfacea and the standardization of the data storage (quantities, format etc.). Some work on the standardization of e.g. data formats was already made in the 1990's [Ano98a], but it is clearly an area were further work is needed.

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16. Microgrids and Smart Grids

Author: Tuomo Vornanen

INTRODUCTION

Traditionally most of the electricity generation has been done by bulk power plants connected to the transmission network and the transmission system operator (TSO) has been responsible for maintaining the power balance and stability. Distribution system operators (DSO) have been responsible for supply of the electrical energy from the transmission system to the consumers. With this objective in mind the distribution networks have been built as cost-effectively as possible. In city centres the distribution networks have been built with underground cables for the last hundred years and have slowly spread to suburbs and even rural areas. The wide-spread electrification of the rural areas of Eastern and Northern Finland began just after the Second World War. Investment costs were major concern for these sparsely inhabited areas and as a consequence the power lines were built straight through dense forests with little concern for reliability.

The domestic electricity consumption has multiplied as electricity usage has broadened from lighting and cooking plates to vast amounts of different electronic, heating and household appliances. Basically, the society is entirely dependent on electricity. This naturally requires more reliable and better quality electric supply service than before.

Public awareness of the effects of air pollution of the power generation and the concern for sufficiency of fossil fuels in the future has led to ever-increasing interest in renewable energy generation. Renewable technologies include solar energy, wind power and various biofuels. In many cases their utilization in electricity generation requires small power plant size, which means that they must be connected to the distribution system instead of the transmission system. As said earlier, the distribution system has not been designed for this purpose. Large-scale introduction of distributed generation (DG) thus requires new innovative solutions in distribution systems.

One key area in reducing emissions is traffic. It seems probable that wide-scale introduction of plug-in hybrid electric vehicles and fully electric vehicles is reality in near future. Since their batteries would likely be charged in residential areas, electricity distribution system faces another new challenge. The problem of charging of large number of electric vehicles is one of the most important obstacles in the large-scale introduction of EVs.

DEFINITION AND PURPOSE OF SMART GRIDS

In source [10] Smart Grid is defined as the means to modernize the existing electric power system, so that it the grid automatically optimizes the various interconnected elements from the central power plants to the end-users thermostats and other appliances. A smart grid has bi-directional electric power and information flows.

The benefits of the smart grid are listed as below [10]:

- Increased reliability and power quality
- Increased electrical safety and cyber security
- Increased energy efficiency
- Reduces greenhouse gas emissions and air pollutants
- Reduces operation costs.

In [12] it is said, that the introduction of Smart Grid technology would decrease the annual disturbance costs to US economy by about 50 billion dollars and reduce the investment costs by 50 to 120 billion dollars before the year 2030.

One key objective is to reduces emissions. There are several possibilities to achieve this. Smart grid should enable easier and cheaper interconnection of distributed generation units using renewable energy sources. Local cogeneration units improve energy efficiency. Intelligent load control, including smart charging of electric vehicles, is used to control loads in order to reduce the need for inefficient coal- or oil-fired peaking power plants or to reduce distribution level overloading. Energy storages can also be used. [10, 12]

Electric infrastructure in general is aging, which means relatively large portion of the electric system has to be upgraded in future. At the same time capital and material costs are increasing. These factors require more efficient utilization of the existing network and power plants. [12]

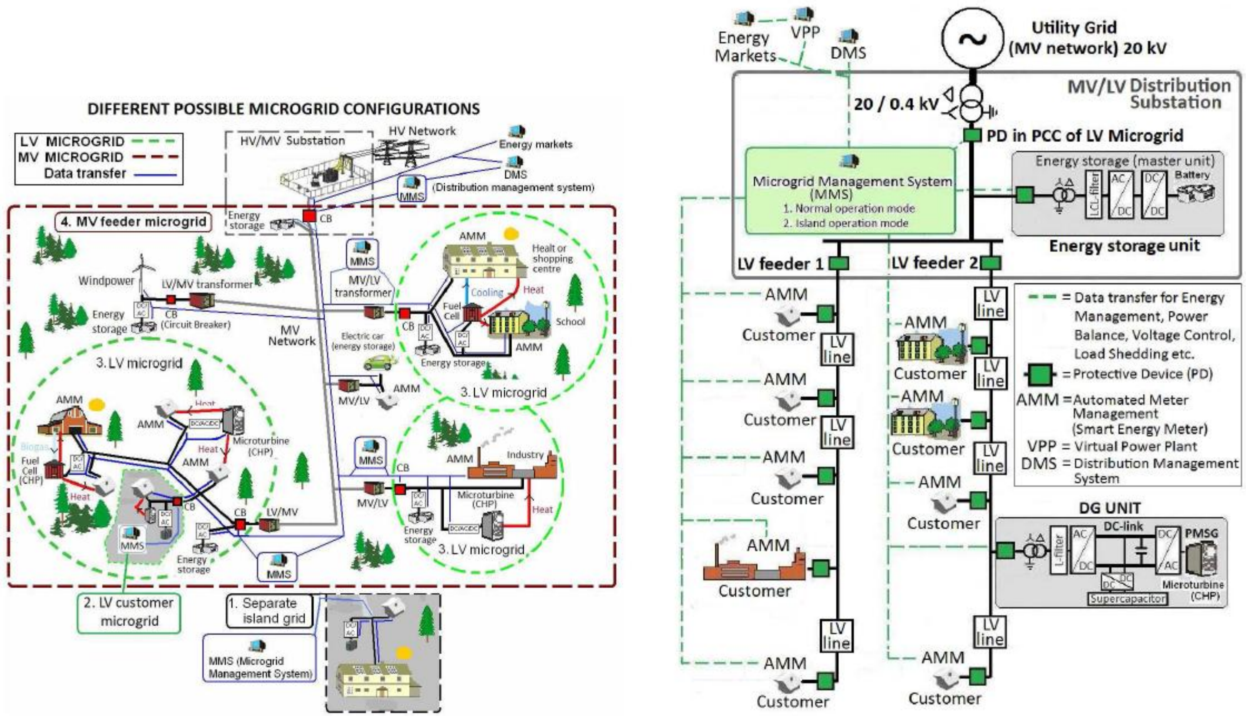
Fossil fuels, especially oil and natural gas, are going to become too expensive to use, when fuel reserves become ever fewer. Smart grid reduces dependency on imported fossil fuels, improving national energy self-sufficiency.

Smart grid technologies may offer other benefits for electricity consumers. Direct economical benefits include savings in energy costs if some of the consumption can be guided to off-peak hours with reduced hourly electrical energy prices. Consumers may have ability to control their energy usage with building automation. Consumers with distributed generation benefit from the ability to sell surplus energy to the utility grid. [12] This is especially beneficial with feed-in tariffs.

MICROGRIDS

One definition for the microgrid is, that a microgrid is a combination of several micro sources, which operate as an independent power system. Instead of connecting a few independent micro sources to the network, they are combined to a single entity, that appears to the grid as one controllable load. When normal distributed generation has a loss-of-mains protection to prevent unwanted island operation, a microgrid is designed to separate from the utility grid, with little or no disturbance to the customers of the microgrid or without hindering the protection of the utility grid. [6, 8]

A microgrid is often defined to consist a single low voltage network or some feeders of it. However, a microgrid might also be a house-level network or even a MV feeder. An example of different microgrid configurations is shown in figure 1 below.



a) b)

Figure 1. a) Different microgrid structures, b) a low voltage microgrid [7].

World-wide, several research projects about microgrids have been carried out. According to [1], the CERTS microgrid concept is a new approach in integrating distributed generation to the electric distribution system. Thus for the electric utility the main benefit of the microgrid is the good behaviour; it’s electrical impact or harm on the utility grid is no higher than that of the normal customers, either during normal operation or in the utility grid faults. Potentially, the microgrid could even support the utility grid, like preventing or postponing grid upgrades by feeding active or reactive power during peak loads. Customers’ benefits of the CERTS microgrid are uninterrupted power supply and better power quality during utility grid disturbances, like voltage sags.

In some sources small-scale cogeneration (micro-CHP) is seen as the essence of the microgrid concept. In that case the microgrid provides both heating and electrical energy for its customers. The source [2] mentions the local combined heat and power that is seen as one of the best alternatives to improve energy-efficiency. Since heat transfer is not economical for long distances, micro-CHP is seen as the answer. The microgrid is built around the concept of the cogeneration, that also offers other benefits, such as the island operation with the UPS function. In both sources [1] and [2] the key finding is aggregation of several micro sources and cogeneration. While the island operation is listed as a major benefit for the customer, the essence is clearly the distributed generation with renewable energy sources, including cogeneration.

In previous sources [1-2, 6, 8] combining larger amounts of micro sources as a single controlled grid was seen as the essence. However, the island operation capability itself might worth of upgrading a low voltage network to a microgrid. Intended island operation with back-up diesel generators has been seen as an alternative to underground cabling of the MV network or back-up connections in rural areas [9]. Microgrid concept could be regarded just a large UPS system. Data and telecommunications centres, many industrial facilities and services have UPS systems. In western societies people have grown accustomed and dependent on reliable electric service and this likely increases in future. The development of electric vehicles and battery technology may enable a wide-spread introduction of battery-storage based large UPS systems or microgrids.

There are several starting points, from which forming of a microgrid can start. For example, a certain low voltage network may have abundant amounts of distributed generation, that it may become beneficial for the customers to upgrade their low voltage network to a microgrid, with island operation capability. On the other hand, the utility company may benefit, when several different micro-sources can treated as a single entity. On the other hand, a low voltage network without any DG might be upgraded to a microgrid to have uninterrupted supply of electric power. In this case the reliability is the driver and the energy sources may a simple battery storage with back-up diesel generators for longer interruptions. Load shedding can be used to reduce the required power and energy capacity of the battery.

In many ways, the microgrids that have been developed in several countries in Europe, Asia and North America, is a parallel and overlapping concept with the Smart Grid. The basic idea is to promote the use of renewable energy by integrating large number of small energy sources them into a single entity.

TECHNICAL ISSUES IN MICROGRIDS

Operation modes

A microgrid has four operating modes, two steady-state and two transient states. The normal operation mode is the grid-connected mode, where a microgrid takes power from the utility grid or feeds excessive power. In island mode the microgrid operates as an autonomous power system, maintaining frequency and voltage with its own active resources. The two transient states are the islanding and re-synchronizing. [5] From these four states the transition to islanding mode is perhaps the most challenging to achieve, because there the need for transition comes suddenly and the microgrid has to stay stable with as little voltage fluctuations to customers as possible.

Connection interface

To achieve high power quality in the microgrid during the utility grid disturbances, the connection interface between the microgrid and the utility has to have fast control. A traditional solution is a circuit breaker, which is a reliable, efficient and cost-effective device. A solid-state switch would be more sophisticated and faster with better voltage quality during disturbances. It would be more costly and have higher energy losses. Examples of connection interfaces are shown in figure 2. [5]

A power electronic converter (AC/DC/AC) would enable accurate output voltage control and reactive power control to the utility grid side. It would offer the best voltage quality during the outage, since the DC link would offer a natural short term energy storage, that could filter out voltage sags. An energy storage could be connected to the DC link using a simple DC/DC converter, while other interfaces would require an additional inverter (DC/AC) for the battery storage. A full-power converter has highest investments costs and conversion losses. [5]

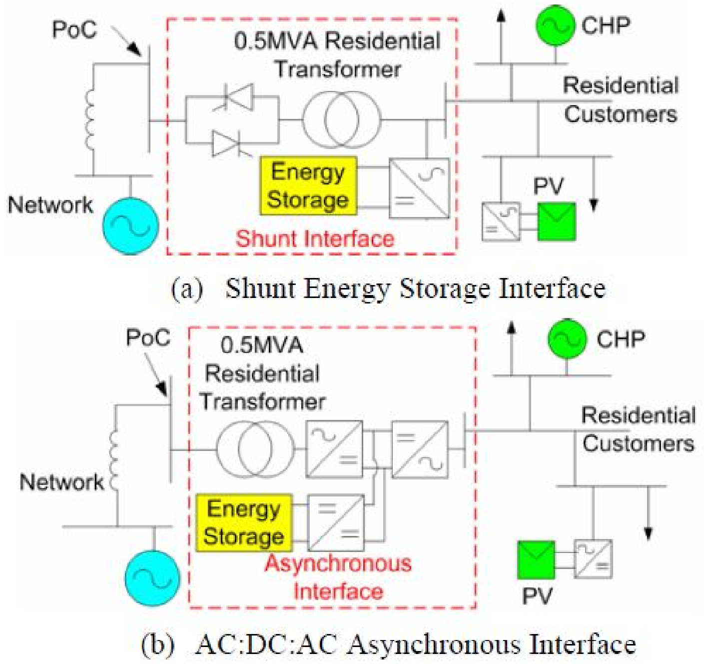


Figure 2. Microgrid connection interfaces [5].

Control of the microgrid

To achieve efficient and economical power generation, a microgrid has a central control system (energy manager) to dispatch various micro sources and to determine how much power should be taken from the utility grid. Intermittent generation, such as PV cells and wind turbines, generate as much electricity as is available from their primary energy sources. The electric power output of the cogeneration units can be controlled to some extent, the long-term energy balance is determined by the need for heating energy.

To achieve stable operation during island operation, a microgrid needs voltage and frequency control. In sources [3-6] several possible voltage and frequency control methods are described, of which some methods are briefly introduced below. There are two alternative methods.

a) Master – Slave Control (or Single Master Operation)

In Master – Slave Control the microgrid has one voltage source, while other energy sources can be controllable current sources or operate PQ mode, producing constant power. Power generation between these energy sources is controlled by a central supervisory control. This method requires good communication system.

b) Multi Master Operation

More redundancy can be achieved if there are several parallel voltage source inverters (several masters). This allows more flexible addition of new micro sources to the microgrid. Each micro source has its own microcontroller, which controls the power output according to locally measured voltage and frequency.

In [6] it is suggested that a microgrid with large number of micro sources needs local voltage control. Since impedances between sources may be small, care must be taken to prevent large circulating reactive currents. A voltage-reactive current droop is proposed, where the voltage set point would be increased or decreased based on the reactive current fed by the source to the microgrid.

However, as said in [3], LV networks have high R/X ratio. This means that the active power equals to voltage drop in the magnitude, while reactive power transfer causes difference in the power angle. Paper [3] suggests that the battery inverter should use PU and Qf-droops.

Active resources

The active resources in a microgrid include distributed generation units, energy storages and controllable loads.

For island operation a microgrid needs a fast energy source to feed or absorb power in power fluctuations. This can be a single or several generators or energy storages. The most numerous generation units are likely to be solar panels, wind turbines and cogeneration units. Cogeneration units may have several different prime movers, such as diesel or gas engines, microturbines or fuel cells. If there are not enough dispatchable cogeneration, diesel aggregates and energy storages can be used, too.

In cases where a microgrid is seem economical or necessary for the improved reliability, the structure can resemble a normal UPS system, instead being a cluster of small micro sources. Perhaps the most simple solution is to connect a battery bank near the connection interface to maintain voltage and frequency during transient faults and short interruptions. A diesel generator increases the operation time as an island, time being limited by the size of the fuel tank.

Island forming, protection in island operation and re-synchronizing

Microgrid protection system must work both in grid-connected and island modes. In case of a utility grid fault, the microgrid must be rapidly isolated. For microgrid faults during island operation one question is how many protection zones are used within the microgrid.

Short circuit fault currents decrease dramatically during the island operation and normal fuse protection of the LV networks may not work adequately. Power electronic converters cannot provide high fault currents. Alternative protection methods, such as zero sequence detection, may be used. [6] Island forming and re-synchronizing back to the main grid are perhaps the biggest challenges of the microgrid control.

DC Microgrids

An alternative for a microgrid based on normal AC voltages is a DC microgrid. There have been a few research projects on DC distribution and DC microgrids. In Japan, researchers of Osaka University have been studying a ± 170 V DC microgrid for residential houses [11]. Each house has its own gas engine or fuel cell to generate heat, while electricity is fed to the microgrid. DC distribution has been studied also in Politecnico di Milano in Italy. An example of DC microgrid is shown in figure 3.

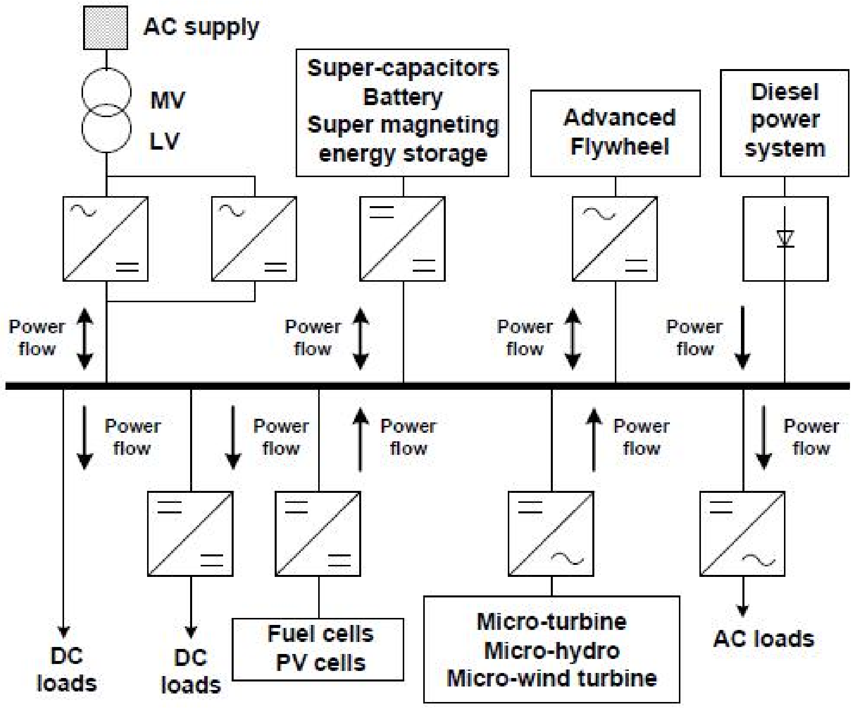


Figure 3. An example of a DC microgrid [11].

The major benefit of the DC voltage in a microgrid is the more simpler converter between a micro source and the microgrid. PV cells, batteries and fuel cells need only a DC/DC-converter, while microturbines with high frequency AC output need a rectifier. On the other hand, some loads can be directly connected to the DC bus.

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17. LVDC distribution and novel inverter technology

Author: Jenni Rekola

INTRODUCTION

Structure of the electricity distribution network is changing. There will be more distributed generation like wind farms and solar power and more energy reserves like super capacitors and batteries connected to the distribution network. Good power quality is more important nowadays because customers are dependent on undisturbed power supply. Low voltage direct current (LVDC) distribution is one possibility to guarantee high power quality to all customers.

Low voltage direct current (LVDC) distribution is a new voltage distribution concept. Medium voltage is decreased to low voltage by a transformer and rectified to DC. Voltage is converted back to AC near the customer.

Low Voltage Directive 2006/95/EC enable to use 1500 V DC in power transmission [1]. Target of the system is high cost-efficiency and reliability [2, 3]. The power transmission capacity of DC is bigger than AC with the same conductors because of the higher voltage level [4]. Losses of the energy distribution are smaller, because all of the power is active power and there is not skin effect on DC cables [3]. Part of the medium voltage network can also be replaced by low voltage direct current distribution because of high power transmission capacity and lower construction and cable costs [5].

Distributed generation and energy reserves are easier to connect to DC than AC in the low voltage network [2,6,7]. Some of the distributed generation technologies, like photovoltaic cells and storage systems, like batteries, generate DC power [2,6]. Therefore these are easy to connect to LVDC network by DC-DC-converters. Efficiency of the system is better because there is less AC/DC and DC/AC conversion stages. Wind turbines are also easy to connect to LVDC network, because there are no frequency synchronization problems [2].

The power quality is better in LVDC network than in the present AC distribution network [4, 6, 7]. Customer’s voltage can be kept almost constant by the inverter. Voltage dips, fluctuations and short-time drops reduce [6]. If a short circuit occurs on one load side, it does not affect the other loads [7]. The DC system enables to compensate voltage sags and short interruptions in the medium voltage network [4] thereby the DC voltage can decrease for example 25 % without any affects on the customer voltage [5]. Every LVDC-distribution network is autonomous protection area. This is very important, because nowadays more than 90 % of the failures, which customers suffer, are caused by failures in the medium voltage network. [5]

If a blackout occurs in the medium voltage network, the islanding operation of the LVDC distribution system is possible [6, 7, 8]. LVDC-distribution system has characteristics of an UPS, guaranteeing the continuity of the service if energy reserves and distributed generation are connected to the network [6].

The efficiency of the LVDC network is complex to calculate. Losses in the cables are smaller than in AC distribution because there are no reactive power and skin effect. The efficiency of the power converters is very high, 95-98 %, at full load but it is much less at partial loading. An efficiency of the converters is about 50 % at 10 % partial loading [3]. Transformers have high efficiency, about 97 %, under full as well as partial loading conditions [3]. The customer’s electricity consumption varies in very large scale and most of the time the converters operate under partial load conditions. If the losses of the converters reduce, the total system losses decrease using DC. [3, 9] Power converters life expectancy should also be longer in the LVDC system. Power converters should stand environmental conditions when these are installed outside. [5]

Efficiency of the LVDC system would grow if some loads are fed by DC. Number and size of the inverters will be reduced if large loads like heating systems are fed directly by DC. Large amount of home electronics use DC and these would be feed directly by DC without AC/DC-converters. [2, 6]

Electrical protection systems of the LVDC network can be integrated into the power converters. Energy metering can be integrated into the customer’s inverters and this enables producing more flexible prices in the energy market. Separate AMR (automatic meter reading)-meters are not necessary. The telecommunication link is connected between the customer’s inverters and the information system of the local electrical network company. [5]

LVDC distribution is an economically potential option compared to traditional network technologies. Prices of power electronic components are decreasing and technical progress is very rapid. The reliability of power electronic devices is improved. More detailed measurements about the state of the network and behaviour of the customer are more important in the future when the network is more complex because of distributed generation and energy reserves. Measurements and the telecommunication connection are easy to integrate into inverters. The prices of traditional passive components like transformers and passive filters are increasing and the prices of power electronic components are decreasing. [10]

LVDC DISTRIBUTION NETWORK

The structure of the LVDC network is unipolar or bipolar. In the unipolar system rectifiers and inverters are connected to 1500 V DC as presented in Figure 1 a. Two voltage levels, ±750V DC, and neutral are used in the bipolar system. The system can be fed by one rectifier which is connected as a bipolar connection as shown in Figure 1 b or by two rectifiers which are connected as a unipolar way between positive or negative pole and neutral. Customers are connected between a positive pole (customer A Figure 1 b) or a negative pole (customer B) and neutral as a unipolar connection, between positive and negative poles as a bipolar connection or between positive and negative poles with a neutral connection (customer C) as a bipolar way. [11]

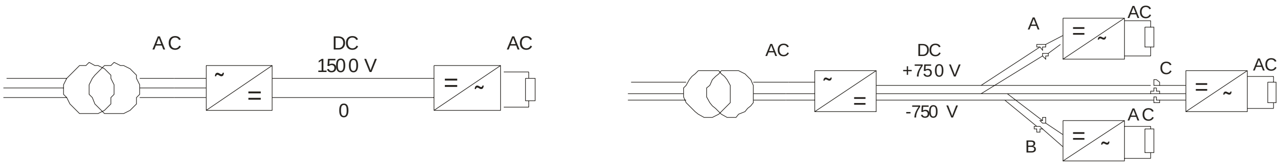


Figure 1. a) A unipolar and b)a bipolar LVDC distribution network

If load inverters are connected as a unipolar connection to one voltage level or single-phase full bridges are used, the electrical network of the customer should be used isolated (IT) or with a galvanic isolation transformer. If load inverters are connected to the LVDC network as a bipolar way and single-phase half bridges or three-phase three-level inverters are used, it is technically possible to use operational grounding (TN) in the customer network without galvanic isolation. [5]

This study concentrates on the bipolar LVDC-distribution. Present low voltage underground cables are possible to use up to 900 V DC, so these can be used in the bipolar LVDC-system. (SFS-4879, 4880, 5800, 5546). The bipolar system provides the use of inverters with a 750 V rated voltage and these inverters are cheaper compared to a 1500 V rated voltage inverters. The bipolar system is more reliable, because it enables an opportunity to keep the other half of the network in operation even if there is a fault in the other half of the network. [11, 5]

Standards and power quality in the LVDC network

LVDC network needs to be secure and reliable. There are many standards which LVDC distribution network has to fulfil. The most important standards are SFS EN 50160 about power quality and SFS 6000 about electrical safety. As already mentioned Low Voltage Directive 2006/95/EC enable to use 1500 VDC in power transmission [1]. Medium-voltage network 20 kV voltage has to lay down by transformer to 1 kV before LVDC distribution [12]. Voltage is DC voltage if its ripple voltage is under 10 % of the nominal voltage [12].

Nominal frequency of the customer’s voltage has to be 50 Hz. In the normal operating conditions the average frequency in the 10 seconds metering time have to be 50 Hz ± 1 % during 99,5 % time of the year. Frequency has to be always 50 Hz +4 %/-6 %. Customer’s voltage has to be sinusoidal and the rms-voltage has to be 230 V. In the normal operating conditions the rms-voltage in the 10 minutes metering time have to be 230 ± 10 % during 95 % time of the week. Rms-voltage has to be always 230V +10 %/-15 %. [12]

Total harmonic distortion (THD) of the supply voltage can’t over 8 % when calculating up to 40. harmonic component. THD is defined in the standard EN 50160 up to 40. harmonic component

$$THD_{2kHz} = \sqrt{\sum_{N=2}^{40} \left(\frac{U_{n,rms}}{U_{1,rms}} \right)^2} \qquad (6)$$

Where U1,rms is the rms-value of the fundamental component of the voltage and Urms,n is the rms-value of the nth frequency component of the voltage. There is also defined the maximum values to every single harmonic component (order numbers 2..25) which are not allowed to overstep according to the standard EN50160. [12]

The power converters in the LVDC network need to fulfil many requrements. Converters should have good dynamic properties and ability to switch off input current without high switching overvoltages. Converters have to be protected against overvoltages and lightning surges. Converters need to be resistive loads from the medium-voltage grid point of view (power factor 0,9 -1). Converters are not allowed to produce lot of harmonics to the medium voltage network neither to the customer's network. [3, 5, 13]

There should be protection devices for the internal faults of the power converters and protection devices which prevent overloading of the power converters. Converters have to handle short-circuit currents of the network and it have to be able to supply short-circuit current which fuses and protection relays need for reacting. [5]

PRESENT DC DISTRIBUTION

DC distribution is used nowadays especially in high voltage applications. HVDC power transmission systems are used for the bulk transmission of electrical power. For long distance transportation HVDC is less expensive and transmission losses are smaller compared to AC-transmission. Especially in undersea cables high capacitance cause high losses if AC-transmission is used. HVDC transmission is also used with offshore wind farms. The cost efficient idea is to use HVDC link to transmit the energy of the wind turbines to onshore and connect the wind farm thought the HVDC link to the AC grid. [14, 15]

DC transmission is used also in low voltage levels. For example in the telecommunication equipment 48 V DC is used. In data centers DC is used because of better efficiency when DC/AC and AC/DC conversion stages are reduced. [9, 15]

Photovoltaic cells and fuel cells produce DC power so there is DC links created to connect all cells together and the total produced power is converged to AC by one common converter. One large DC/AC-converter is more cost efficient to use than many smaller ones. Also in the industry applications some common DC link systems are used, which feed many DC motors. [14]

DC is used in shipboard systems, where medium voltage DC is converged to lower DC level or to AC. In traction systems, communication networks, aircraft and automotive power industry DC is used as well [2, 9, 14, 15].

Power generated by photovoltaic cells and wind turbines is increasing very fast. At the same time also the number the home electronic devices which use DC is increasing. At this point of view, it is very logical, that LVDC distribution concept is very interest research topic at the present time.

Number of conversion stages will be reduced, the efficiency of the network will be better and the network system will be more reliable. [4, 7, 8, 15]

RESEARCH OF LVDC DISTRIBUTION

LVDC distribution concept has been studied during the last few years especially in Finland (Tampere University of Technology and Lappeenranta University of Technology), Italy, Japan and Belgium.

The number of DC power consuming devices has increased very fast during the past few years in the homes and offices. These are for example computers, printers, battery chargers and other home electronics. Researchers are analyzed, would it be more efficient to use DC distribution in house electrical installations. Number of power conversion step size will be reduced, but DC/DC converters are still needed, because devices need different DC voltage levels to operate. The most important criteria which affects to the efficiency of DC home installations is the efficiency of the power converters. If the efficiency of the power converters would be over 95 % also at partial load conditions, the DC installations might be more efficient than present AC system. The efficiency of the system would be much better, if LVDC-distribution is used at the same time and if customers have some own distributed generation which is connected to the DC network. [14]

Engelen et al. have done theoretical analysis about efficiency of LVDC distribution and using DC in house installations. 600 V DC voltage level is used in the LVDC network and DC levels 20 V, 230 V and 325 V are used in house installations. The unipolar structure of the LVDC network is used. The bipolar power flow is not needed, because the distributed generation is used only to peak shaving of the power consumption. According to theoretical analysis and simulations, the LVDC distribution system would be more efficient than the present AC system if the efficiency of the power converters is almost as high as transformers. [3]

The bipolar LVDC-network is analyzed in Finland, in Italy and in Japan. The basic structure of the network is almost the same in all these cases, but the DC voltage level is different dependent on the local standards. In Finland ±750 V DC is used, in Italy ±400 V DC is used and in Japan ±170 V DC. The structure of the LVDC system by Japanese researchers is presented in Figure 2. In Italy and Japan two-level three-phase converter is used between medium voltage network and the LVDC network enabling bipolar power flow. Distributed generation and energy reserves are connected to the DC network. Because the structure of the system is bipolar, the balance converter needs to be connected to the DC network to stabilize the two voltage potentials. [2, 4, 5, 6, 7, 8, 11, 16]

Customer's loads are connected to the DC network by DC/DC converters or DC voltage is converged to AC by two-level one-phase or three-phase inverters. According to simulation and measurement results with the laboratory prototype, the LVDC system can preserve its stability even if there is some disturbance in the medium voltage network or in some customer's network. A short circuit accident at one load side does not affect the power supplying to the other loads. [2, 4, 5, 6, 7, 8, 11, 16]

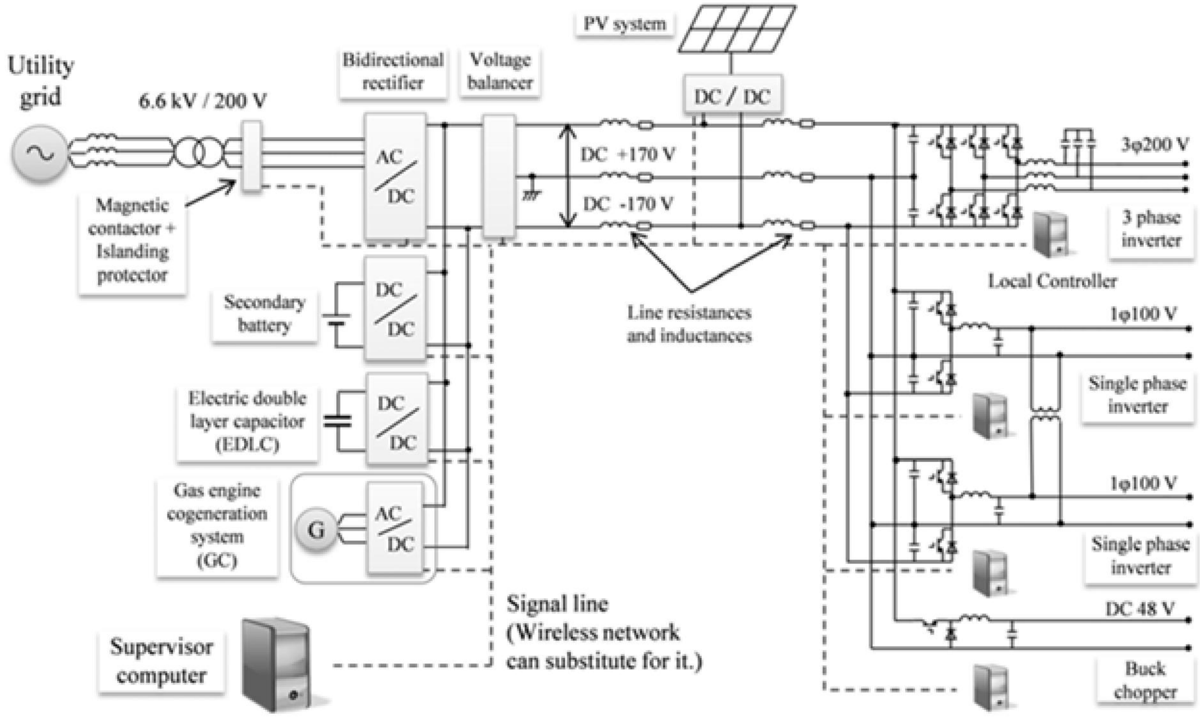


Figure 2. Structure of the LVDC network [16]

The target of the LVDC system is to use the converters by power factor one, make bidirectional power flow possible and ensure the high quality power transmission to the customers. The efficiency of the network should be as high as possible. Remarkable prototype installations are not done. All research is concentrated on theoretical analysis, simulations and small-scale laboratory prototype installations. One of the most challenging research questions of the LVDC network is the protection system. All present protection systems, like fuses and automatic relays are not possible to use with power converters, because power converters can't produce short-circuit current high enough. Research questions about protection, safety and grounding of the LVDC system should solve before it is possible to construct large scale prototype installations. [2, 4, 5, 6, 7, 8, 11, 16]

In the paper [17] is presented the idea of local DC network, which voltage level is 318 V DC. The voltage is produced by photovoltaic cells, fuel cells or the medium voltage is rectified to DC. Batteries are also connected to the network to increase the reliability of the system. There is a controller in the DC/DC converters of the photovoltaic cells, which stabilizes the DC voltage level of the network.

DC distribution is analyzed also in some special applications. For example [18] is presented, that lightning system is possible to replace by DC LED lights and DC voltage in lightning systems. The DC system would be more cost efficient.

THREE-LEVEL CONVERTERS IN LVDC DISTRIBUTION

Power electronics are the key enabling technology to realize LVDC network and all other smart grid or microgrid visions [19]. These provide advanced technical features, such as independent control of active and reactive power, the capability to supply weak or passive networks and less space requirements. Security and communications systems can be integrated to the power converters. [19] Converters can be controlled external by communication system. [13]

This study concentrates on three-level converters in LVDC distribution. Three-level converters are widely used in medium- and high-voltage level because of smaller voltage stress of the power semiconductor switches than in two-level converters [20, 21]. Three-level converters are not yet used commercially in low-voltage level because of more complex structure and higher costs. Three-level converters and other multilevel converters are studied a lot during the past few years because these enables smaller ripple in the output voltage and decreased total losses of the converter. Better power quality, smaller passive filter components and high efficiency are more and more important in the future.

There are many different three-level converter topologies. One of the most common topologies is the three-level neutral-point-clamped voltage source converter [21]. This topology, also known as NPC-converter is used in this study. Principle of operation and the structure of NPC-converter are presented at first time already in 1981 [22].

One-phase half-bridge NPC inverter is presented in Figure 3. It consists of four power semiconductor switches, four antiparallel-connected freewheeling diodes and two clamping-diodes. There have to be two capacitors in the DC-intermediate circuit, because clamping diodes are connected in the middle of the DC capacitors.

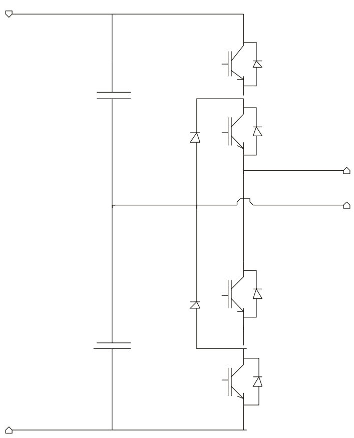


Figure 3. One-phase half-bridge NPC inverter

Three-level converters give many advantages compared to two-level converters. There are more switches in three-level converter, but the maximum voltage stress of the power semiconductor switches is udc/2. The maximum voltage stress of the power semiconductor switches is double, udc in a two-level converter. [20, 23, 24]. Because of the smaller maximum voltage, also the switching losses are smaller [20].

Harmonic content of the output voltage and current is small, because there are three voltage levels (udc/2, 0 and – udc/2), instead of two, in the output voltage when using three-level converter. High-frequency losses are small [20, 23, 24, 25] and there is no need for du/dt-filter in the converter terminals [20, 25]. Semiconductor stress is reduced due to small current ripple [23]. Switching frequency can be lower compared to two-level rectifier or filters can be smaller and lighter [20, 23, 25]. This is very important, because passive components are a substantial reason to weight, cost and losses in power converters [20]. Also resistive losses in the cables and transformers are lower because of the small harmonic content of the voltage and current.

Conduction losses of the three-level converter are bigger than in two-level converter, because there are two switching devices in the current path [20]. In spite of that, the total semiconductor losses are smaller with three-level converter when the switching frequency is above 4 kHz [20]. Because of the smaller losses also the cooling unit of the three-level converter can be smaller than in two-level converter [20]. Three-level converters have high efficiency also in partial load operation and that is why these are used for example in wind power applications [20].

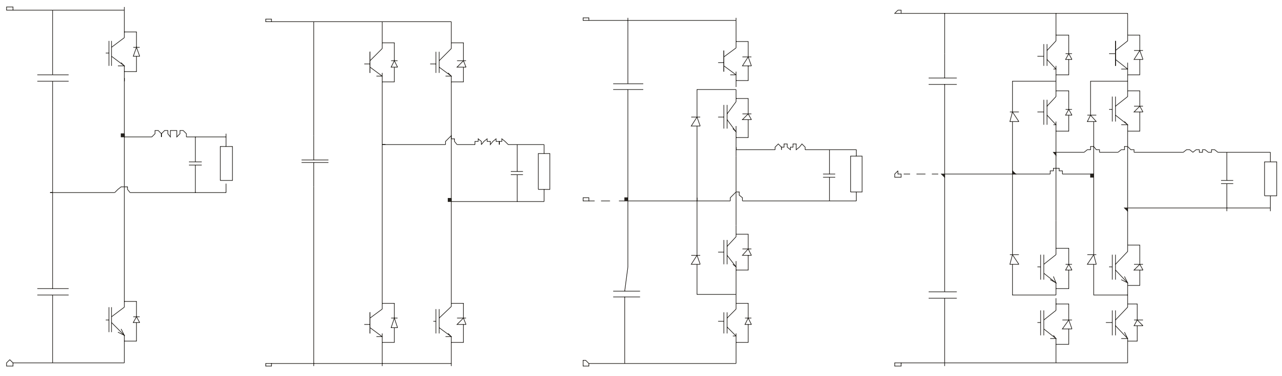
Common-mode voltage of the three-level converter is 25-30% lower than in two-level converter [20, 25]. Absolute values depend on the operating point and modulation scheme of the converter [20]. There are less bearing currents, bearing failures and EMI-problems with three-level converters because of lower common-mode voltage [20, 23].

Life-expectancy of the three-level converter is at least as long as two-level converter. There are more semiconductors in three-level converter but failures happen in semiconductors rarely. Usually the converter broke because of failures in passive components and fans. [20]

It is possible to use many different converter topologies in LVDC distribution. Diodes, thyristors or IGBT-component can be used in the rectifiers and inverters. The most simple rectifier topology, which is possible to use in LVDC-distribution, is 12-pulse half-controlled thyristor-bridge. Half of the components are thyristors and the other half are diodes. 12-pulse half-controlled thyristor-bridge is now used for example in HVDC-applications. Three-level Vienna-rectifier gives more possibilities to control the DC current and it doesn't produce low frequency harmonics to the MV network. It is possible to control the power factor of the MV network by Vienna-rectifier. It consists of three IGBT-components and 18 diodes. Only unidirectional power flow is possible by diode-, thyristor- and Vienna-rectifiers. [5, 11]

Bidirectional power flow and better power quality in the LVDC network is possible to realize by using two- or three-level converters. DC voltage must be sufficiently greater than the peak value of the input voltage in order to prevent the overmodulation of the converter [4]. Large amount of distributed generation is possible to connect to the LVDC-network. The power flow direction is easy to control in the LVDC network based on current flow. This is the most important advantage of the LVDC network in comparison with AC systems according to [13]. Active converters can inject reactive power into the medium voltage network to control the power quality of the medium voltage network [13]. LVDC distribution network looks like resistive load to the medium voltage network when the power factor is one. It is possible to control the amplitude of the DC voltage by two- or three-level converter. DC voltage is easy to control, because only the voltage level is important, not shape and frequency of the voltage [13]. Two- or three-level converter can compensate disturbances present in the medium voltage network [6].

The customer needs DC-voltage, one- or three-phase AC-voltage. One-phase AC-voltage is possible to produce by two- or three-level single-phase half or full bridges. Three-phase AC-voltage can be produced by three-phase two- or three-level inverter. Single-phase load inverters are presented in Figure 4.



a) b) c) d)

Figure 4. Single-phase two-level a) half bridge, b) full bridge and three-level c) half bridge, d) full bridge

This study concentrates on comparing different converter topologies in LVDC-distribution. Target of the work is to find out, which topologies are the most technically and economically suitable options to LVDC distribution. Control methods of the converters are also analyzed during the study and the efficiency of the LVDC network is trying to be maximized. Connection of distributed generation and energy reserves to the LVDC network will be analyzes as well.

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