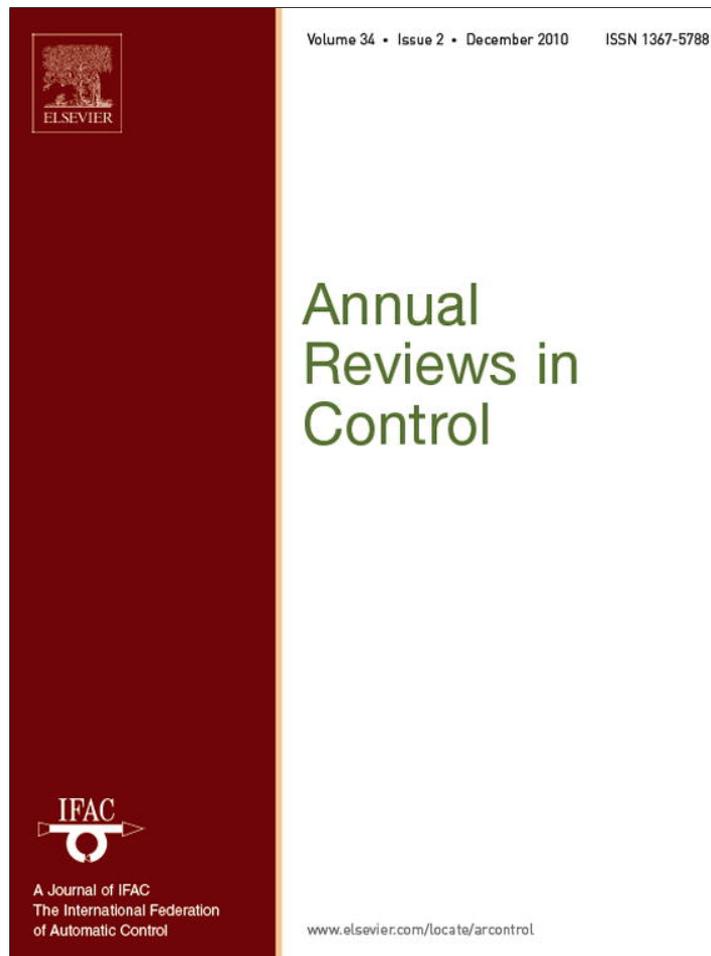


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journal homepage: www.elsevier.com/locate/arcontrolSmart grid power system control in distributed generation environment[☆]Pertti Järventausta^{a,*}, Sami Repo^a, Antti Rautiainen^a, Jarmo Partanen^b^a Tampere University of Technology, P.O. Box 692, 33101 Tampere, Finland^b Lappeenranta University of Technology, P.O. Box 20, 53851 Lappeenranta, Finland

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ABSTRACT

This paper discusses the general aspects of smart grids and focuses on some distribution level smart grid features, such as interconnection of distributed generation and active distribution management, using automated meter reading (AMR) systems in network management and power quality monitoring, application of power electronics in electricity distribution, plug-in vehicles as part of smart grids, and frequency based load control as examples of interactive customer gateway.

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1. Introduction

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

- The penetration of distributed generation (DG), especially based on Renewable Energy Sources (RES), will continue due to environmental reasons.
- The European and North American vision is to have common electricity market areas with a high penetration of distributed power generation.
- Efficient use of energy at customer level and intelligent demand response has become an essential issue.
- 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.
- There is a need, due to economical reasons, to increase the utilization rate of existing networks. The traditional way of

developing a distribution network would be to invest in passive wires which would lead to a decrement of the utilization rate.

- Many components of existing networks are reaching the end of their life cycles. They need replacement or continuation of their lifetime in a safe and controlled way.
- Regulation of network companies will tighten up while companies want to ensure the profitability of their business. This will mean rationalization of network management both in short- and long-term perspectives.
- The risk of major disturbances is increasing, both the probability and the consequences. The reason for this increased probability is the complexity of the power network and the increased failure rate due to climate change. The consequences are increasing due to society's higher dependency on power supply.

There is a vast amount of research, as well as many visions and concepts concerning the future power delivery system; super grid, smart grid, micro grid, intelligent grid, active network, power cell, etc. Some of them focus on transmission level functions (e.g. integration of large-scale wind power or utilization of controllable devices) and some cover low voltage level and customer interface (e.g. large-scale advanced AMR). The concepts have many common features but also some differences, which are not analysed more deeply here. The main approaches to fulfil the above needs are still the same. A shared vision of smart grid, or a corresponding concept, is an important issue in order to develop commercially successful and useful products for a future power delivery system. This vision should be shared by network companies, product vendors and network customers.

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This paper focuses mainly on general aspects of smart grids at distribution level and gives examples of some smart grid functions and features.

2. Challenges for the distribution system

Electricity distribution networks create a market place for small-scale power producers (i.e. distributed generation) and for customers (i.e. users of electricity). Here, the role of distribution networks is of great significance. For example in Finland, about a half of the total price of electricity for small customers and over 90% of all interruptions come from the distribution process. There are many challenges for the distribution system to enhance its functionality as the real market place, as follows:

- improving the capability to serve the increasing amount of distributed generation,
- enabling electricity market development at customer level, e.g. to enhance market-based demand response and customer-oriented services,
- safe and cost-efficient operation of distribution networks in all circumstances.

Traditionally power generation, distribution network management and loads have been considered as quite independent processes. Along with an increasing amount of distributed generation, the traditional approach is gradually changing. A considerable amount of renewable energy resources represent distributed generation, but also active energy resources such as loads, storages and plug-in hybrid vehicles will be increased. One of the main barriers for the penetration of active resources at distribution network level is the complexity of the interconnection process. From the network management point of view the increasing amount of DG is often considered reluctantly as it brings the complexity of a transmission network to distribution network level. The main reason for the complexity is caused by the present methods for managing the distribution networks as well as the features of different active resource components themselves, which are not sufficiently developed to enable easy interconnection. So far loads and customers have been passive from network point of view. By making the customer connection point more flexible and interactive, the demand response functions (e.g. by real-time pricing, elastic load control) are more achievable and the efficient use of the existing network and energy resources by market mechanisms can be improved.

3. General features of smart grids

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 (i.e. direct current). Active resources (i.e. distributed generation, loads, storages and electricity vehicles) actually change the traditional passive distribution network to be 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.

Smart grids can be characterized as follows (partly based on Chuang, 2008):

- interactive with consumers and markets,
- adaptive and scalable to changing situations,
- optimized to make the best use of resources and equipment,

- proactive rather than reactive, to prevent emergencies,
- self-healing grids with high level of automation,
- integrated, merging monitoring, control, protection, maintenance, advanced IT systems, etc.,
- having plug-and-play features for network equipment and ICT solutions,
- secure and reliable.

A traditional grid includes centralized power generation, and at distribution level one-directional power flow and weak market integration. Smart grids include centralized and distributed power generation produced substantially by renewable energy sources. They integrate distributed and active resources (i.e. generation, loads, storages and electricity vehicles) into energy markets and power systems. Smart grids can be characterized by a controllable multi-directional power flow.

Smart metering has been seen as an essential part of the vision of smart grids. A remotely readable energy meter is being developed to be a piece of intelligent equipment (i.e. an interactive customer gateway) including, in addition to traditional energy metering, different kinds of new advanced functions that are based on local intelligence. This gateway opens possibilities for network companies, energy traders and service providers to offer new kinds of added-value services to end customers.

The concept of smart grids may be characterized by words like flexible, intelligent, integration and co-operation. Grids are flexible because they utilize controllable resources throughout the network. Respectively, a passive network has flexibility by network capacity, i.e. the network itself may handle all probable loading conditions. Intelligence is simply investments on in protection, controllability and information and telecommunication technologies instead of pure passive lines, cables, transformers and switchgears.

DG and existing controllable resources like direct load control, reactive power compensation and demand side integration are good potential controllable resources for the smart grids. The integration of DG and flexible loads in a distribution network will benefit the network when managed appropriately. The traditional passive network management or the “fit & forget” principle in DG connection needs to be changed into active network management. The integration of DG and other active resources into a distribution system is required in order to fully exploit the benefits of active resources in network management. With proper management of active resources the overall system performance may be improved from presently used practices.

One important control task in power systems is to maintain balance between power production and consumption which means keeping the power system's frequency at an appropriate level. This process is becoming more and more challenging due to an increase in the penetration level of intermittent power production, for example wind and solar power. In recent years there have also been many serious frequency instability related wide-area power system blackouts in Europe and USA, and their costs, both economical and social, are high.

4. Active distribution management

4.1. Impacts of distributed generation on distribution network

The production of electricity close to consumers will reduce the transfer of electricity. This will also affect network losses. Network losses may also increase when a large DG unit, e.g. wind farm, is located far from consumption and the electrical distance of transferred electricity increases compared to a situation without a DG unit.

The intermittent (non-dispatchable, uncertain and uncontrolled) production connected into the passive network does not

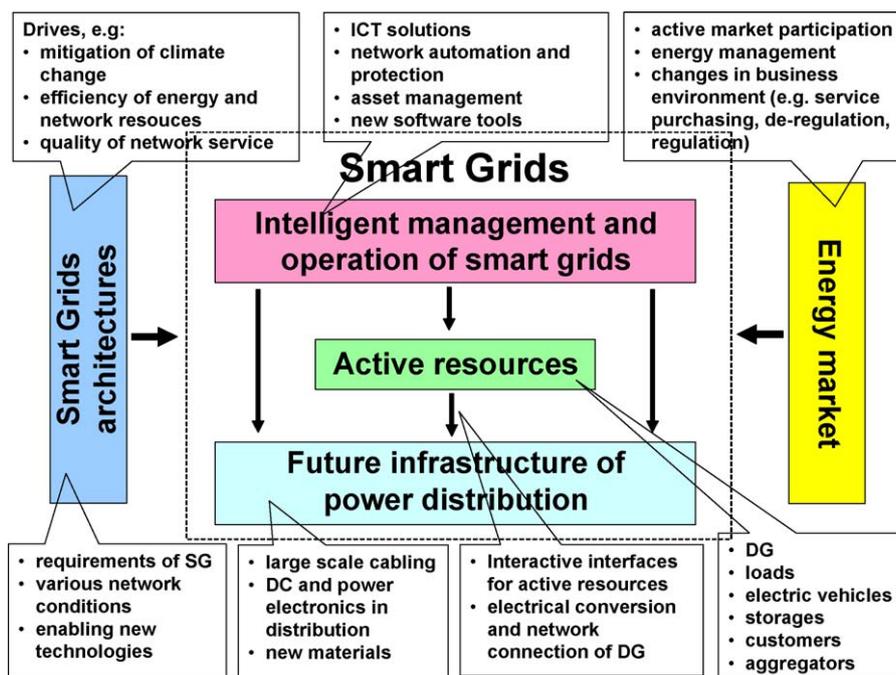


Fig. 1. Aspects of smart grids.

benefit network rating. The load ability of a distribution network is determined by voltage profile (decrease or rise), power quality and thermal ratings. The intermittent production in a weak rural distribution network may cause voltage rise problems. The dimensioning of the network becomes quite challenging when there are different sizes and types of DG units along the network. The worst case planning principle of DG interconnection in passive networks should be replaced with a statistical planning approach in active networks (Repo et al., 2005). The increment of fault current level due to new DG units may cause investments in networks if the rating of components is exceeded. The voltage control or reactive power capability of DG units could also be utilized in network management.

Requirements for the protection of distribution networks are changing considerably (Mäki, 2007). Protection schemes designed for unidirectional power flow may become ineffective. Unnecessary tripping as well as undetected faults or delayed relay operations may occur due to high DG penetration. DG may also disturb the automatic re-closing. The operation sequence of protection devices during a fault is thus important. Due to DG, the existing methods used in a fault location could also become inappropriate.

The current operational practice of a distribution network requires the disconnection of DG units when a fault occurs. This will keep the operational conditions simple and clear, safe and suitable for auto-reclosing. The purpose of DG unit connection point protection (e.g. frequency and voltage relays) is to eliminate the feeding of fault arc from a DG unit and to prevent unintended island operation. When the penetration level of DG increases, the consequences of an immediate tripping of DG units may become adverse when a short-circuit in transmission grid is seen by several DG units. Even during a fault at a distribution network unnecessary disconnection of DG units may occur due to unwanted trips of feeder or DG unit protection relays, loss of synchronism of synchronous generators, sustained over-speed and over-current of asynchronous generators or over-current and DC over-voltage of power electronic converters. The current operational practice clearly creates a contradiction between network safety and

stability. However, the consequences of stability issues for the whole power system and also for DG owners and other distribution network customers are becoming more important when the disconnection of DG units may cause system wide stability or local power quality problems.

4.2. ADINE project for active distribution management

A joint demonstration project called ADINE financed by the 6th Framework Programme of the European Commission, Priority 6.1 Sustainable Energy Systems is in progress (ADINE, 2007; Repo et al., 2008). The partners of the project are ABB Oy Distribution Automation, AREVA Energietechnik GmbH, AREVA T&D Ltd., ComPower AB, Lund University, Tampere University of Technology, and Technology Centre Hermia Ltd. as the coordinator. The project is under execution between October 2007 and September 2010.

The aim of the ADINE project is to develop new methods for distribution network management including DG. When a distribution network is managed according to the ANM (i.e. active network management) method the interactions of different active network devices can be planned and controlled to benefit the operation and stability of the network. One feature of this project is that it develops and demonstrates the ANM method and the enabling solutions simultaneously. The project will develop and demonstrate:

- protection of distribution network including DG
 - application of communication based relays at distribution network,
 - fault location with the influence of DG,
 - co-ordinated protection planning application on Network Information System (Mäki, 2007).
- voltage control of distribution network including DG
 - droop control of small-scale micro-turbine,
 - co-ordinated voltage control application at control center level which controls the setting values of local voltage/reactive power controllers (Kulmala et al., 2007).
- new-generation medium voltage STATCOM (static synchronous compensator)

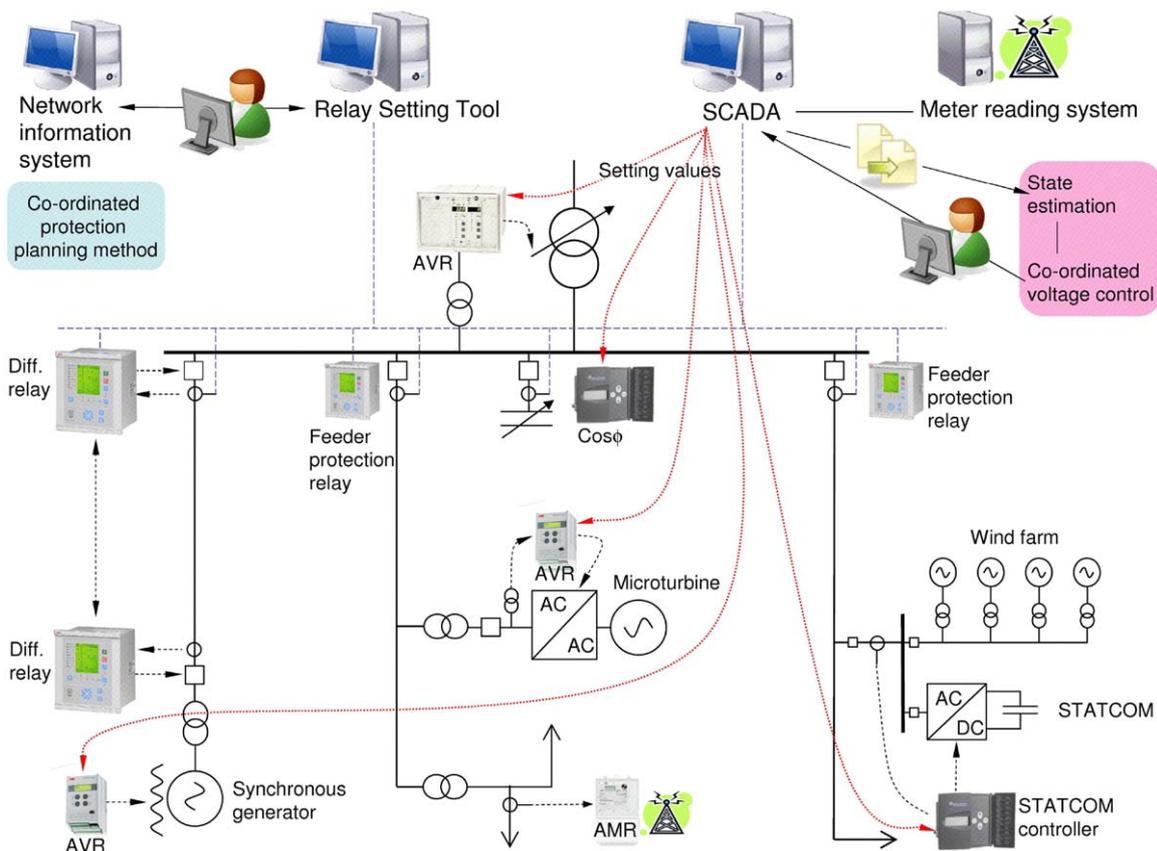


Fig. 2. Overview of the active distribution network in the ADINE project.

- capable of filtering harmonics, eliminating flickers and compensating reactive power (Lauttamus and Tuusa, 2008),
- on top of above characteristics, it can participate in mitigation of voltage dips and in controlling the voltage level of the distribution network.

Fig. 2 visualizes the control levels of distribution network and how the ANM method is affecting them. All hardware devices are basically working on local level. They get measurements from local measurement devices and operate based on this information. It is a decentralized operation of protection and control similar to present day operations. However, the locations of protection and control devices are not limited to primary substations but they may be located along the distribution network. Some control devices may also be located on a customer owned active device like DG or STATCOM. Protection relays work on the lowest level like in passive networks, but new feeder protection schemes such as directional over-current, distance and differential protection, and new fault location applications are introduced. Automatic voltage regulation (AVR) of DG units, AVR of main transformer, STATCOM controller and power factor controller are added to the automatic control system level.

The new issue in ANM is the utilization of automatic control systems in distribution network operation. Demonstrations will show how the protection and voltage regulation in distribution networks can be improved through advanced protection schemes and decentralized control of DG units.

The ANM method is a conceptual description of the management of an active distribution network. It is capable of applying any communication medium and protocol but is however restricted by capabilities of individual devices and software. Naturally the whole system would be cheaper, simpler, and more scalable, if multi-functional and vendor open interfaces (e.g. IEC 61850) and

data models (e.g. IEC 61970 and 61968) are applied at information exchange.

The ANM method is tested and demonstrated in laboratory environment using real-time digital simulator for electricity network (RTDS) and for power electronics (dSPACE). Some functions have also demonstrated in real distribution network environment.

5. Using AMR in network management

The primary role of AMR (Automatic Meter Reading) systems has been to provide energy consumption data to the utility, but the cost of retrofitting the existing energy metering system may not be justified without added value functions. At present, many utilities at European level are installing large-scale AMR projects. So far the focus of the installations has mainly been on remote reading of energy measurements. Also some specific applications have been developed, e.g. for load control. The comprehensive concept of using AMR system and data in network and electricity market management is still rare.

One requirement for creating additional value functions is the open architecture in AMR systems to provide necessary integration possibilities. Standard integration ways, e.g. OLE for Process Control (OPC) or open connectivity via open standards makes it possible to develop new types of intelligent system integrations.

Traditionally AMR and Distribution Management System (DMS) have been separate systems without any integration with each other as illustrated in Fig. 3. The primary role of AMR has been to provide energy consumption data to the utility for billing and balance settlement purposes. AMR system has also been used for load control in some installations. So far automatic monitoring and control center measures by the DMS have been used mostly for

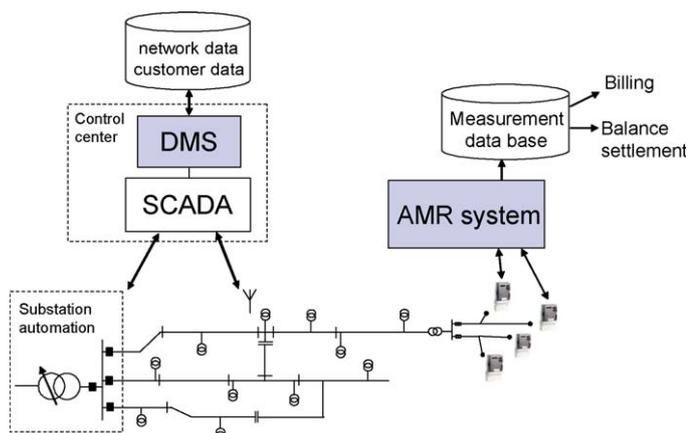


Fig. 3. Traditional way of network management.

operating medium voltage networks. A fault in a low voltage network is cleared automatically by a blown fuse, but no information about that is received to the control center. The existence of a LV-network fault is usually indicated only by customer calls.

The present AMR meters offer the platform (i.e. the infrastructure and communication) to determine and develop new upper-level functions (see Fig. 4). These will be used in developing network asset management, market enhancement and customer service. First implementations of advanced AMR systems 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, alarms based on exceptional events, i.e. network faults and voltage violations are enabled. Meters may also have some protective functions for safety reasons. The use and integration of AMR 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 Fig. 4 illustrates, AMR system can be utilized in many functions of a distribution company, 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 characteristics), customer service, and load control in addition to traditional use in billing and load settlement.

The integrated AMR, DMS and power quality monitoring systems offer information to be used in overall asset management and

network planning. 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. Real-time AMR data can be used in state estimation, but for network planning purposes load models are still needed. For network operation purposes more accurate real-time state estimation of the whole network gives information on voltages, loads, losses, and stressing of components, and also makes it possible to optimize, e.g. network topology, voltage control, and load control actions. In network planning more accurate load models (e.g. more accurate division of customer groups, regional models, etc.) for network calculations and information on realization of power quality (i.e. interruptions, voltage dips, voltage levels) can be used to allocate measures and investments. More accurate information on hourly variation of losses is also valuable for the network company.

5.1. An application to low voltage network fault indication

Low voltage network management may include functions, for example, to indicate automatically if a fuse in the low voltage network has burnt or a conductor is broken, to locate the fault, to provide accurate interruption data, to monitor voltages at the customer site in real-time and provide voltage level as power quality information for customer service.

Traditionally low voltage network management has been in complete off-line mode since on-line information has been available only from primary substations and from some secondary substations along medium voltage feeders as presented in Fig. 3. The integration of AMR makes it possible to cost-effectively monitor a low voltage network and analyze fault situations since AMR communication infrastructure can be used. Network monitoring in SCADA/DMS requires that events from meters are received in a near to real-time manner.

An advanced AMR meter works as an intelligent monitoring device and utilizes the communication infrastructure to provide spontaneous event or alarm information to the control center with vital information on low voltage network faults and voltage levels. The meter includes algorithms to infer the existence of a fault and type of the fault. In certain cases, e.g. when the neutral conductor is broken, the advanced AMR meter may even isolate the customer from the network automatically. This requires a specific switching device which can be integrated into the advanced AMR meter.

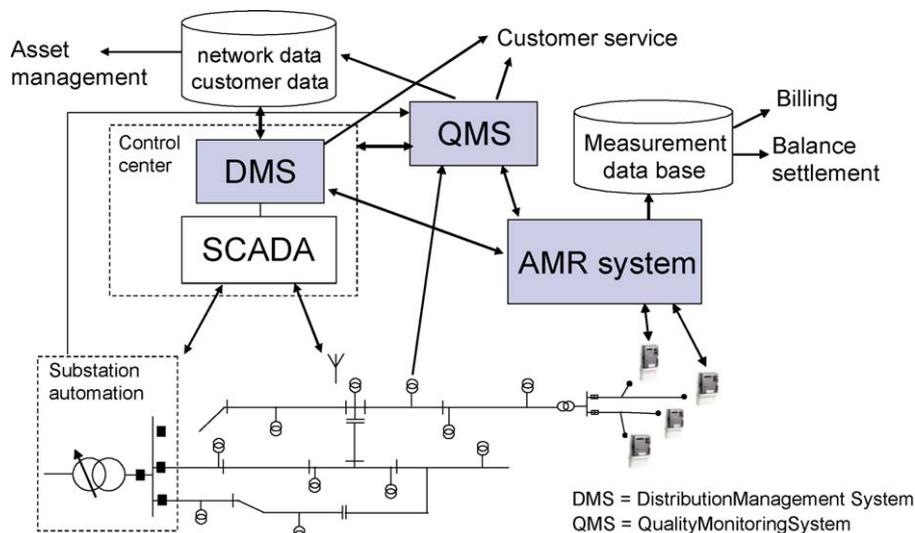


Fig. 4. Integrated information systems for comprehensive network management.

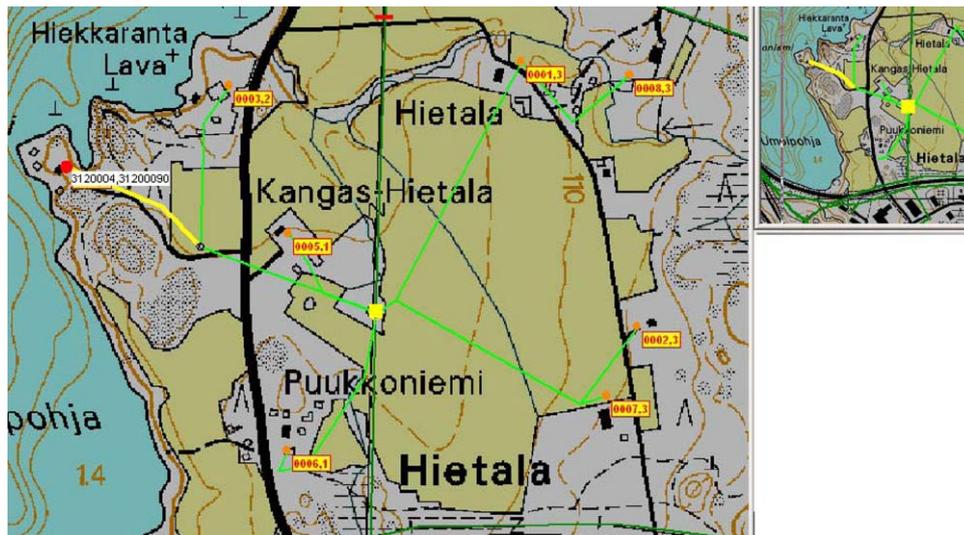


Fig. 5. A case of a broken neutral conductor (Kärenlampi, 2007).

Fig. 5 illustrates a part of the DMS screen in a case of a broken neutral conductor. Network coloring shows the results of the inference to locate the broken line-section.

When event data from meters are combined with a topological network model in the DMS, the original reason or faulted component can be located. This gives enormous benefits for low voltage network management when, for example, blown fuses, broken conductors and voltage problems can be presented to the operators at the control center almost in real time manner.

Above described application is in real use in some Finnish distribution companies (Järventausta et al., 2007).

5.2. Power quality monitoring

At the moment, voltage quality is usually monitored temporarily at customer sites based on customer reclamations, not comprehensively and continuously from the entire distribution network. Power quality monitoring including continuous voltage quality monitoring in a larger extent gives however important information for various operations of a distribution company. The development of systematic procedures for power quality data management supports in general:

- customer services (e.g. quality reports, clarifying customer requests, planning of compensation of reactive power, instructions for the use of various equipment),
- distribution network design and operation (e.g. investment plans and management of voltage drops and fluctuations, harmonics and other disturbances),
- outage statistics (e.g. needs of the Energy Market Authority).

The novel AMR technology makes it possible to integrate basic power quality functions to AMR meter. In addition to registered interruptions with time-stamps, the following quantities for each of the three phases can also be metered depending on the meter configuration: voltage and current variations, active power, apparent power, total reactive power, fundamental frequency reactive power, voltage dips and swells, total distortion of the supply voltage, some harmonic voltages, DC-voltage component, frequency of the supply voltage, voltage unbalance between the three phases (Koponen et al., 2002; Mäkinen et al., 2003).

The idea is to gather information from the low voltage level and integrate it, for example, with network databases and different

planning and operation systems to increase knowledge with much larger amount of information. The measurement data (i.e. even over several years) can be stored in the open relational Power Quality Database (PQDB) (see Fig. 6). The measurement data of the PQDB can be studied using the web-based application in addition to DMS and network planning systems. The use of web-based technology in PQ monitoring may be an internal or an outsourced service for distribution companies. Web-based PQ monitoring is an example of ASP (Application Service Provider) functions (Antila et al., 2005). Power quality data can also be offered to the customers (e.g. industrial customers) with their energy consumption and billing data through the Web.

Factors that increase the need and possibilities of monitoring power quality also on low voltage level are e.g.:

- need for better customer service,
- reasonably priced meters,
- telecommunication development,
- applications which can use the power quality data in network planning and operation,
- regulation requirements.

6. Interactive customer gateway

For developing distribution management and the functionality of the electricity market, one essential objective is to make the customer, or at least customer connection point, active for improving, e.g. interconnection of distributed generation, efficient use of energy, market-based demand response, quality of supply, and management of active distribution networks. A remotely readable energy meter is being developed to be a piece of intelligent equipment (i.e. an interactive customer gateway) including, in addition to traditional energy metering, different kinds of new advanced functions that are based on local intelligence and power electronic applications as parts of active distribution networks. The interactive customer gateway will be based on the use of modern power electronics, advanced AMR technology and two-way communication between databases and applications of the distribution system operator (DSO), transmission system operator (TSO), service providers and electricity energy market players (e.g. aggregators) as illustrated in Fig. 7.

The interactive customer gateway enables (Järventausta et al., 2008):

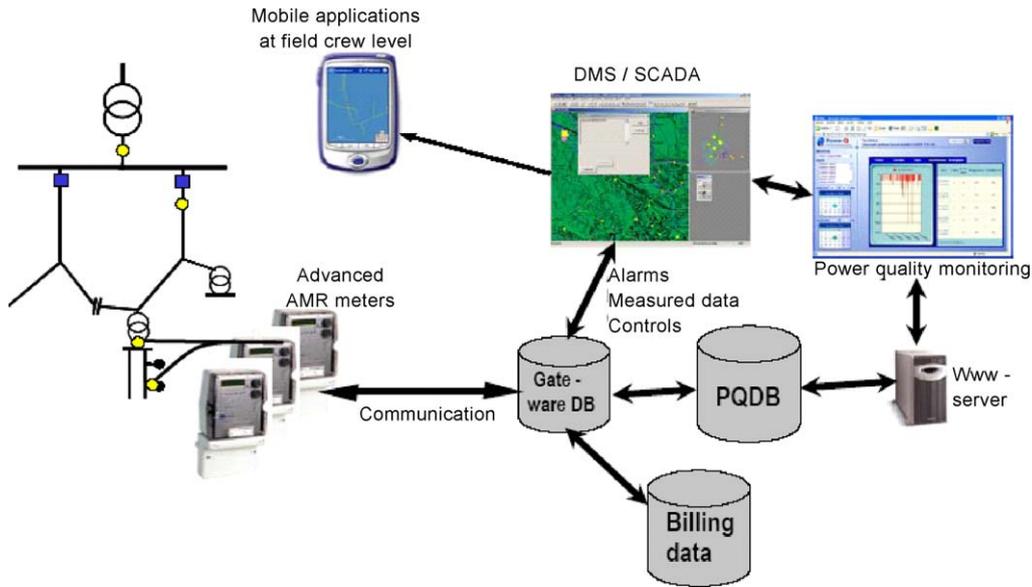


Fig. 6. Realized power quality monitoring as part of integrated information systems.

- more efficient and flexible network interface, e.g. for DG and plug-in hybrid cars,
- on-line market (price) oriented load and DG control management,
- frequency based load control during local or system level load and generation unbalance situations,
- services for energy savings and efficient use of energy,
- on-line management and control of customer voltages, also including elimination of short interruptions (i.e. reclosings and voltage dips),
- more reliable constructions in distribution networks and advanced management of active distribution networks using data on interactive customer gateway.

There are some technology trends which makes it possible to define the customer interface in a brand new way. Large scale AMR implementations are underway or planned in many European countries. At European level visions of smart grids, smart metering has been seen as an essential part of smart grids, especially for interconnection of distributed generation, demand response and

active distribution management. Communication technology and computer systems and their integration are under rapid development. Power electronics has typically been used in high voltage transmission networks, but at the distribution level only some applications have been seen. Traditionally, the customer interface has consisted of bills, customer complaints and an on-site readable energy meter (i.e. conventional kW-m). Now the concept of an intelligent customer gateway enables the customer or the automatic functions related to the customer to be active in network management and in the electricity market based on on-site applications and two-way communication with upper-level applications.

7. Power electronics in electricity distribution

The technical and economic development of power electronics has been fast and continuous. The unit prices for conventional components used in distribution networks, e.g. transformers, have been growing significantly. Meanwhile, the price erosion for power electronics components has been about -7%/year during the past

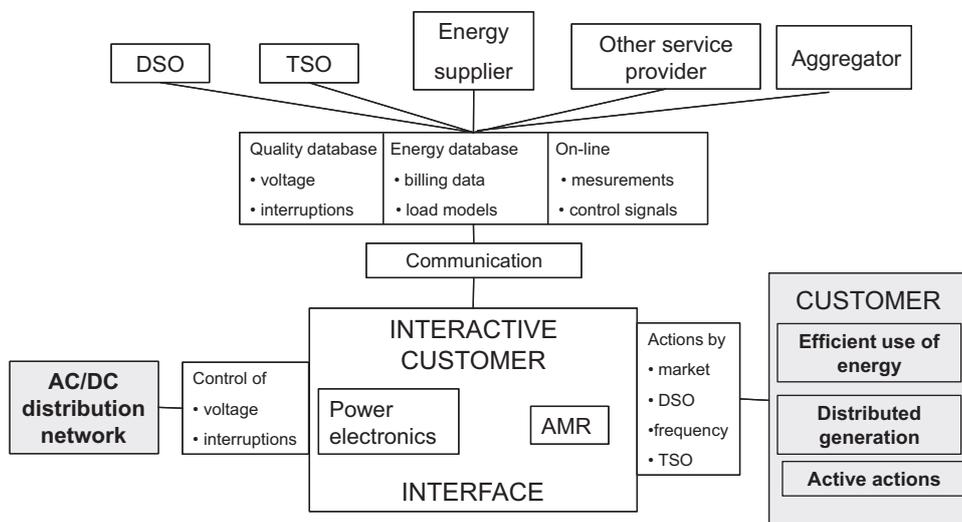


Fig. 7. The concept of interactive customer gateway.

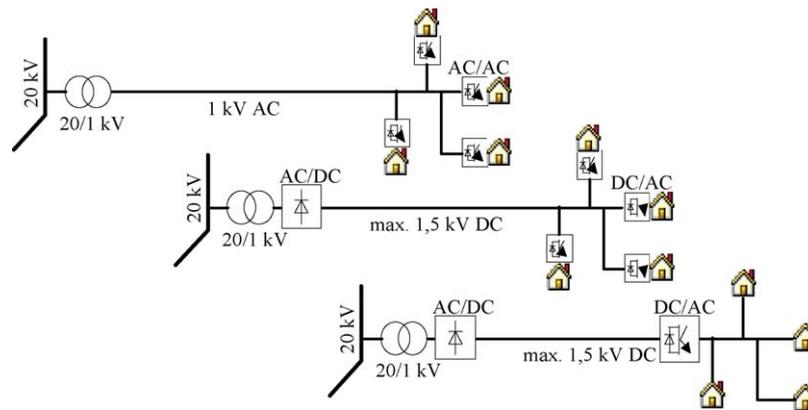


Fig. 8. Possible main principles for power electronics in distribution systems.

decade. This makes it possible to harness the power electronics solutions to serve even the customer interface.

In several earlier studies and reports opinions and visions have been illustrated of the utilization of power electronics in the quality control of electricity supply. Power electronics is already a part of modern electricity distribution, for instance, in network connections of small-scale generation units. In the larger scale, power electronics is still unexploited in actual customer interfaces.

The application of power electronics enables the LVDC (i.e. low voltage direct current) supply in a distribution system. The European Union (EU) low voltage directive (LVD 72/23/EEC) defines the boundaries for the low voltage levels used in public distribution systems. It covers equipment designed for use with a voltage rating between 50 and 1000 V in alternating current supply and between 75 and 1500 V in direct current supply. The use of DC-voltages, e.g. ± 750 V DC, dramatically increases the power transmission capacity of low voltage networks and makes it possible to connect small scale generators without more expensive medium voltage installations. Fig. 8 illustrates the way power electronics may be applied in distribution networks. More detailed descriptions and results are given, e.g. in Kaipia et al. (2008) and Lassila et al. (2009b).

A power electronic based customer interface improves the quality of supply significantly. The voltage will be a constant 230 V independent of load variations. Short interruptions can be eliminated, too. Intelligent power electronics opens new tools for demand side management. E.g. the local control of voltage can be used to decrease the loads. There is also the possibility to connect some loads (e.g. ovens) directly into the LVDC supply.

Practical questions are related to customer level converters, DG-converters and the technically and economically optimal voltage levels to be used in DC-supply. Electrical safety questions and overall fault protection of the LVDC system are essential study topics, too.

8. PLUG-IN vehicles as part of smart grids

Transportation has a very important function in today's society. Globally, the energy production of transportation systems is almost completely oil dependent. The transportation sector is also a significant consumer of energy and a significant source of greenhouse gases and other emissions. 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 great potential to fulfil these challenging requirements.

This creates a challenge to the existing electricity distribution infrastructure. Depending on the electric car charging methods, the

power demand may increase dramatically or stay almost at the present level. The existing electricity distribution infrastructure sets some limitations to the large-scale adoption of electric cars. Without any intelligence included in the system, the charging of electric cars may increase the peak power much more in comparison to the present load level even though annual energy needed by the car is still low (i.e. some thousand kW) (Lassila et al., 2009a).

Plug-in vehicles (PHEV and EV) could also be used to produce different kinds of ancillary services to control and manage the electric power systems as a whole.

8.1. Frequency dependent charging

As a part of the above mentioned interactive customer gateway, frequency dependent charging can also be developed (Rautiainen et al., 2009a, 2009b). In this case the control method of the battery chargers is based on local frequency measurements carried out in the vehicles' grid interfaces. Control based on local measurements is an effective way to utilize a large number of distributed resources which have to react to frequency disturbances in a very dynamic manner. Frequency dependent battery charging can be used to enhance power system's frequency regulation capacity (which operates in normal grid conditions), to enhance power system's disturbance reserves (which operate in abnormal grid conditions) or to enhance both of these. One way to make a charger frequency dependent is to control the charging power directly in accordance with frequency. The simplest way to realize this is to stop the charging (regarding those chargers which are charging) when grid frequency falls under a predetermined level, or in some cases the charging can begin (regarding those chargers which are not charging and which are engaged with a non-full battery) if frequency rises to a high enough level. Power can also be controlled in a continuous manner as a function of frequency. In Fig. 9, this principle is illustrated in three different appliances: frequency regulation, disturbance reserve and a combination of these two.

In frequency regulation application, when frequency varies at interval $f_1 \dots f_2$, power drawn from the grid by the charger is varied continuously at interval $P_{c1} \dots P_{c2}$. At nominal frequency f_n a charger draws power P_{cn} . In frequency regulation application chargers regulate their power demands in frequency interval which is accepted as normal variation. For example, in Nordel (i.e. Nordic interconnected transmission grid) interval $f_1 \dots f_2$ could be 49.9 ... 50.1 Hz. Varying charging power causes some uncertainty in the charging time of the batteries, and interval $P_{c1} \dots P_{c2}$ should be limited so that charging of the vehicle is not disturbed too much. The frequency regulation application could support the power balance related to some renewable energy resources which are of

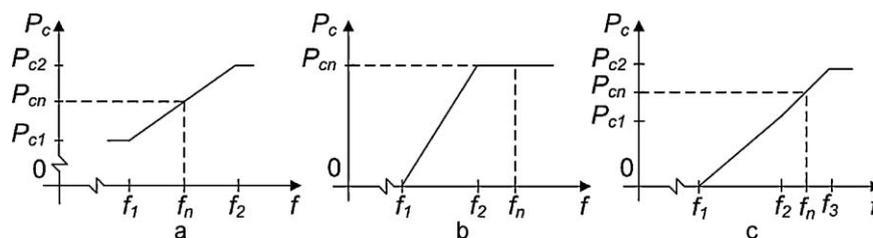


Fig. 9. Controlling charging power in accordance with frequency in (a) frequency regulation application, (b) disturbance reserve application, and (c) combination application (figure is not in scale).

intermittent nature, for example wind power and solar power. The disturbance reserve application is illustrated in Fig. 9(b). The figure only presents the operation in low frequency area, because over frequency disturbances are not usually a problem in large-scale power systems (Anderson and Mirheydar, 1992). In this application, the charger does not react to small frequency declines. When frequency falls low enough, the charger starts to reduce its power and can reduce it down to zero. For example, in Nordel the operation frequency interval $f_1 \dots f_2$ of this application could be 49.5 ... 49.9 Hz. In this application, chargers are set ready to participate in the management of large power unbalances of the grid, and are thus usually fairly rarely used. The combination application, which is presented in Fig. 9(c) combines the two other applications presented earlier. During small frequency deviations ($f_2 \dots f_3$), the charger changes its power within interval $P_{c1} \dots P_{c2}$, and if frequency falls low enough ($<f_2$), power can be cut to zero. More detailed descriptions and simulation results can be found in Rautiainen et al. (2009a, 2009b).

Frequency dependent charging of plug-in vehicles offers an effective way to enhance a power system's frequency stability. Distributed controllable loads offer a resource that can very rapidly react to frequency disturbances, and the harm (charging energy which is not received) to the vehicle users caused by the charging control can be negligible. However, wide utilization of the frequency dependent charging requires economical incentives for the vehicle users or legislative actions. The amount and availability of controllable load depends strongly on many things including plug-in vehicle penetration, driving habits, energy consumption of the vehicles, charging opportunities (including battery replacement service) and charging habits. Plug-in vehicles are not yet widely in the markets, and thereby embedding new functions to the vehicles is technically fairly easy and could be executed at low costs. In the future plug-in vehicles might communicate with different parties via wireless communication networks, and using this gateway the transmission system operator could update the parameters of the frequency dependent controller. Frequency dependency function could also be implemented with vehicle-to-grid (V2G) concept. The use of V2G offers a wider range of operation (for example \pm nominal power) than frequency dependent charging, although it is more complex.

9. Frequency based load control

As a part of the above mentioned interactive customer gateway, frequency dependent space heating can also be developed to manage frequency disturbances in power systems. Setting values of space heater thermostats are made dependent on the locally measured network frequency. Studies are carried out through time domain simulations and also through laboratory testing by implementing a new function to the advanced AMR meter described in Section 5. Studies imply that the use of frequency dependent loads in frequency disturbance management is an efficient tool for managing power unbalances. This kind of load control method's consequences and harm to the users of the space

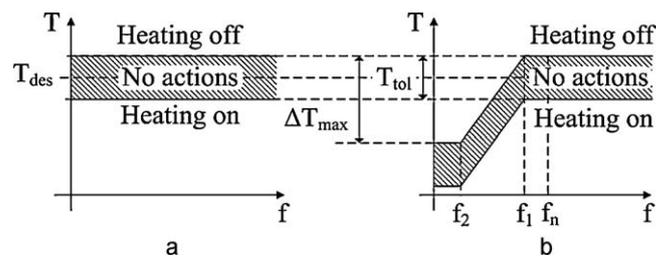


Fig. 10. (a) Conventional thermostat action and (b) control method of frequency dependent electric space heating load used in these studies (figure is not in scale).

heaters can be negligible, but the significance of this controllable load to the power system can be very high. It is very important to coordinate the operation of a frequency dependent load carefully with other control actions taking into account the cold load pick-up phenomenon related to the use of this type of load.

In this case, dynamic demand control (DDC) method, presented in (Schweppe, in press) and further explored in (Short, Infield, & Freris, 2007), is applied to electric space heating loads. In the method, the temperature settings of an electric space heater thermostat are frequency dependent in accordance with local frequency measurements. Fig. 10 illustrates the control method of the loads used in the study. Fig. 10(a) depicts normal thermostat action. Heater is switched on whenever temperature falls under certain level, and off-switching occurs when temperature rises high enough. Thereby temperature varies around desired temperature T_{des} , which is set by user of the load through a manual thermostat adjustment. Fig. 10(b) illustrates DDC method in a disturbance reserve appliance. The set point value of the temperature is now a function of grid frequency. Load reacts only at frequencies under f_1 and the maximum temperature deviation from normal operation is set to ΔT_{max} .

More detailed descriptions and simulation results can be found in Rautiainen et al. (2009a, 2009b).

10. Conclusions

This paper discusses aspects of smart grids in general and gives examples on some smart grid functions and features. The paper presents some smart grid features at distribution level dealing with interconnection of distributed generation and active distribution management, using automated meter reading (AMR) systems in network management and power quality monitoring, application of power electronics in electricity distribution, plug-in vehicles as part of smart grids, and frequency based load control. A remotely readable energy meter is being developed to be a piece of intelligent equipment (i.e. an interactive customer gateway) including, in addition to traditional energy metering, different kinds of new advanced functions that are based on local intelligence and power electronic applications as parts of active distribution networks. The interactive customer gateway will be based on the use of modern power electronics, advanced AMR

technology and two-way communication between databases and applications of the distribution system operator (DSO), transmission system operator (TSO), service providers and electricity energy market players (e.g. aggregators).

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