Distributed Intelligence in Critical Infrastructures for Sustainable Power
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D3.3. Final Report on Field Experiments and Tests

Cor Warmer, Josco Kester (ECN),
Christophe Andrieu (IDEA), Rune Gustavsson (BTH)
with contributions from all partners

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IDEA	Principal Contractor	France
EnerSearch	Principal Contractor	Sweden
E.on Sverige	Principal Contractor	Sweden
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Document description

This document describes the high level results of the three field experiments and tests performed within the CRISP project.

The aims of the document are the following:

- To give an account of the lessons learned from the experiments as they have been performed.
- To give recommendations for strategic use of intelligent ICT in high-DG power networks (thinking forward from our experience in the experiments).
- To compile 'industrial guidelines and recommendations' for the strategic use of intelligent ICT for various operational aspects of high-DG power networks. These strategic recommendations will not only cover technology issues, but also business, economic, and market considerations. The role of utilities and third parties in utilising this new technology in this changing scene forms an important issue to be dealt with.

Executive summary

This report evaluates the results of the field tests and experiments performed within the CRISP project. From these experiences it gives industrial guidelines and recommendations for strategic use of intelligent ICT in smart power networks of the future. The field tests and experiments show that it is possible to develop a grid architecture for a smart power network of the future. By using the latest information and communication technologies, this new grid architecture makes it possible to operate power networks with a high degree of distributed generation (DG).

In the CRISP experiments the focus was on a specific set of relevant practical situations, issues and scenarios such as:

1. **Market-oriented supply-demand matching** to increase the cost-effectiveness of DG network operations, by integrating demand-side and supply-side management through online agent mediated e-markets, that exploit real-time price/cost information as well as knowledge of load/supply needs and profiles connected to the user's primary process.
2. **Online distant supervision, fault detection and recovery** of distributed networks including generation and controlled loads, ensuring robustness of the system performance, including the possibility of “self-healing” of the network under major disturbances and blackouts, through automatic reconfiguration, by means of distributed intelligence.
3. **Intelligent load shedding in emergency situations** such that cost-controlled and prioritised load shedding is done in much more fine-grained ways than currently possible.
4. **Multi-agent system based methods for online integration and massive coordination**, to compensate for the intermittent character of renewable energy supply, and to increase the value of added flexibility of storage, which achieve bottom-up rather than the usual hierarchical top-down optimisation.
5. **Architectures and requirements for distributed intelligence in highly distributed power networks** that recognise and cope with the fact that such networks contain different decision-making levels of granularity (end-customer devices, low-voltage last mile access and distribution, middle-voltage grid operations) and therefore are inherently treated as networks of networks themselves.

These themes were addressed in the following three CRISP experiments:

- Experiment A: Supply and Demand Matching, performed by ECN and supported by ENECO, in the Netherlands. This field test mainly focuses on the issues 1 and 4 above;
- Experiment B: Fault detection and recovery, performed by IDEA in France and BTH in Sweden. This experiment mainly focuses on issues 2 and 5 above;
- Experiment C: Intelligent Load Shedding, performed by E.on Sverige, Enersearch and ABB in Sweden. This field test on the island of Öland mainly focuses on issue 3.

Two unique aspects of the CRISP project are:
1. that intelligent ICT strategies for both normal and emergency operations in highly distributed power networks are investigated;
2. that two large scale field tests are performed, in both Sweden and the Netherlands.

During the implementation of the CRISP project we have witnessed the large international blackouts of 2003 with follow up assessments and recommendations. As a consequence the CRISP project has had an increased focus on issues related to dependable and secure embedded ICT architectures to support future cell-based virtual utilities.

From the evaluation of the field tests and experiments we conclude that state of the art ICT components can be applied to introduce distributed intelligence in the power network. Distributed ICT architectures combined with intelligent agents are indispensable fundaments in the control of large-scale dispersed generation in the grid. The flexible cells allow fast adaptation of the grid to critical situations.

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1. Introduction

1.1. The CRISP project: objectives and investigated issues

The CRISP project has investigated, developed and tested how latest advanced intelligence by ICT technologies can be exploited in a novel way for cost-effective, fine-grained and reliable monitoring, management and control of power networks that have a high degree of Distributed Generation and RES penetration.
The opportunities for interactive power networks create new possible control mechanisms that bring about flexibility and a feasibility of self-managing networks. Both normal and emergency operations have been investigated, covering different time scales. Insight in performance, security and architecture of highly distributed systems has been made available. Technical availability, functionality and economic cost-benefit considerations have also been integrated. The disseminated results will contribute to better regional monitoring and control of local distribution in the EU-network.

In the CRISP project three application areas are integrated into an environment for control of forthcoming power systems with a large share of distributed generation, as has been depicted in Figure 1-1.

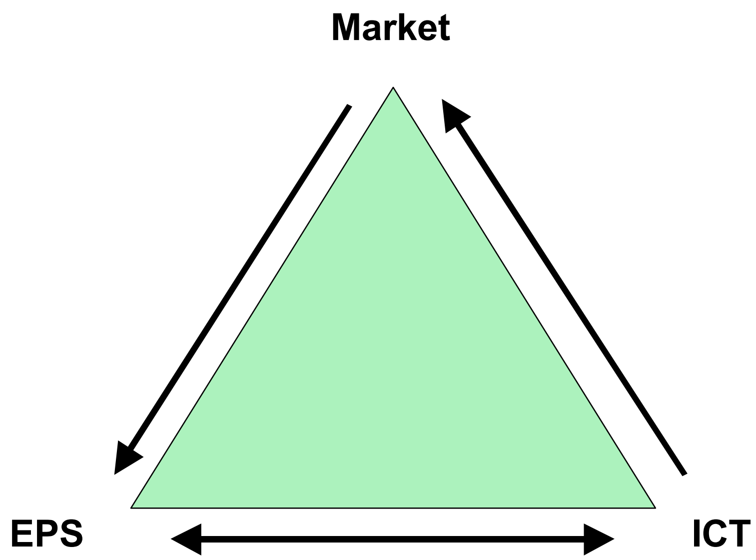

Figure 1-1 The CRISP "market - EPS - ICT" triangle

The Electrical Power System (EPS) traditionally has been managed in a highly centralised way. Distributed generation and penetration of RES at the distribution level of the power system will require new ways of control in which distributed intelligence needs to be applied to mimic the distributed energy resources in the future grid. Information and Communication Technology (ICT) creates universal connectivity between a large variety of grid components and serves as an enabler of bottom-up control of the future power system. ICT thus provides new ways for real-time interaction between suppliers, distributors, and customers in the grid. Automated demand response, balancing services, and dynamic pricing, buying, and selling of power in real time, are just a few of the new services due to the application of advanced ICT. Thus a market-oriented coordination system for supply and demand of electricity emerges. This concept links well with liberalising markets for electricity in Europe,

The CRISP project focuses on three main themes:

- Combining multi-agent systems with microeconomic principles creates a coordination system for supply and demand of electricity in networks with a high share of distributed generation.
- Fault Detection and Diagnosis in innovative grid architectures leads to distributed network operation in which grid cells are managed by agents.

- Intelligent load shedding leads to smooth load relief and reduces in emergency situations the consequences of power system disturbances.

Special attention will be paid to Dependability and Security issues. The future grid architectures consist of the energy system coupled to embedded information systems, so that we have to deal with the interdependencies between two critical infrastructures. Simultaneous protection of critical EPS infrastructures and of critical information infrastructures is therefore a major concern.

1.2. Experiments and Tests

Scenarios and strategies developed, constructed and simulated within this project have been implemented and tested for distributed intelligence in power networks, tools and components in several experiments, laboratory and field tests. There have been three different major groups of tests and experiments led by industries in three different countries.

- ECN, supported by ENECO, has led experiment and test group A performed in the Netherlands;
- IDEA together with BTH has led experiment and test group B performed in France;
- ABB SA together with E.on Sverige has led experiment and test group C performed in Sweden.

Supply-demand matching reduces regulating power needs (ECN, supported by ENECO, Netherlands)

The ECN field experiment on supply-demand matching (SDM) particularly refers to the scenarios and strategies concerning market-oriented supply-demand matching and associated highly distributed architectures. The aim of the SDM mechanism, baptized the PowerMatcher, and developed within this project, is the coordination of supply and demand of electricity in networks with a high share of distributed generation. The specific aim of the field test is the reduction of imbalance in an electricity portfolio, caused by a deviation of actual electricity supply and demand from the predicted electricity supply and demand, especially the case of intermittent supply by wind. Another main aspect is to test the ICT elements needed for implementation of the PowerMatcher mechanism in a real-life environment.

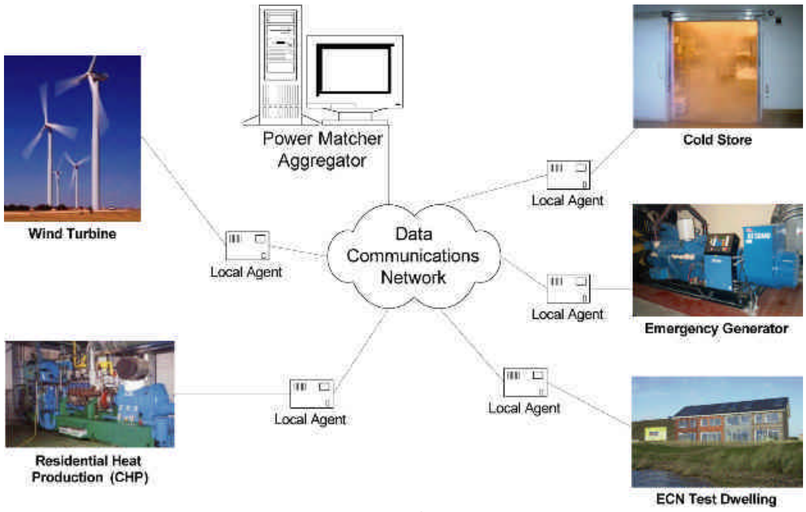

Figure 1-2 Electronic market experiment for automatic supply-demand matching

One application is to combine different distributed and renewable energy resources in a commercial cluster. Electricity producers and traders have to forecast their production and consumption on a daily basis and communicate this to the transmission system operator (TSO). The total demand and supply must be in balance on the market as a whole. The TSO compensates deviations that occur real-time by contracting regulating power. The costs for this balancing operation are put on those parties in the market that deviate from their forecast. The field experiments show (see also http://www.powermatcher.net/) that agent-based electronic markets in a local or regional commercial cluster are able to reduce a substantial part of such deviations. So, they reduce costs for the market parties as well as the need for regulating power. Massive implementation of this concept will reduce the financial risk of producers and traders and make the grid and the electricity markets much more stable.

Advanced fault detection and handling (IDEA, France)

The IDEA experiment on online fault diagnosis particularly refers to the scenarios and strategies concerning DG system robustness and fault diagnosis. For these several tools, functions and algorithms have been developed and tested, including an application called the Help Tool for Fault Detection (HTFD). The aim of this tool is to prevent deterioration of the system robustness because of introduction of DG. The aims of the tests performed are an evaluation of the performance of the developed tools, functions and algorithms.

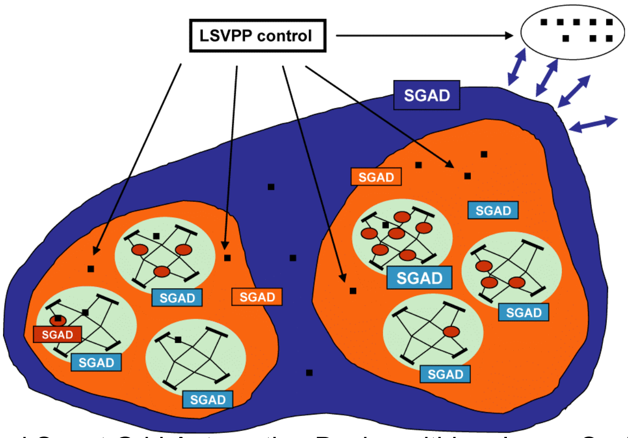

Figure 1-3 Agent-based Smart Grid Automation Device within a Large-Scale Virtual Power Plant

Agents representing a part of the grid are also of use in fault detection, localization, isolation and reconfiguration of flexible cells. This has been shown in recent tests with an agent-based Smart Grid Automation Device (SGAD) that is part of a future large-scale virtual power plant (LSVPP) concept. In a cell of the grid, messages can be exchanged between devices in a few tens of milliseconds. Faults can be isolated correctly in less than 10 seconds up to one minute, even if data communication rates are as low as 10 kbit/s. Hence, this approach drastically reduces the time interruptions observed today on the distribution system.

Intelligent load shedding (ABB, Enersearch, E.On Sweden, Sweden)

The E.ON / ABB / EnerSearch experiment on Intelligent Load Shedding particularly refers to the scenarios and strategies concerning intelligent load shedding and network security issues in emergency situations. The aim of this application is to minimise load shedding actions during an imminent emergency situation, and still prevent an EPS blackout. The aim of the tests performed for this application was to evaluate the feasibility of an intelligent load shedding system. For this aim, data have been gathered on load and supply characteristics of the power grid of the Swedish island of Öland.

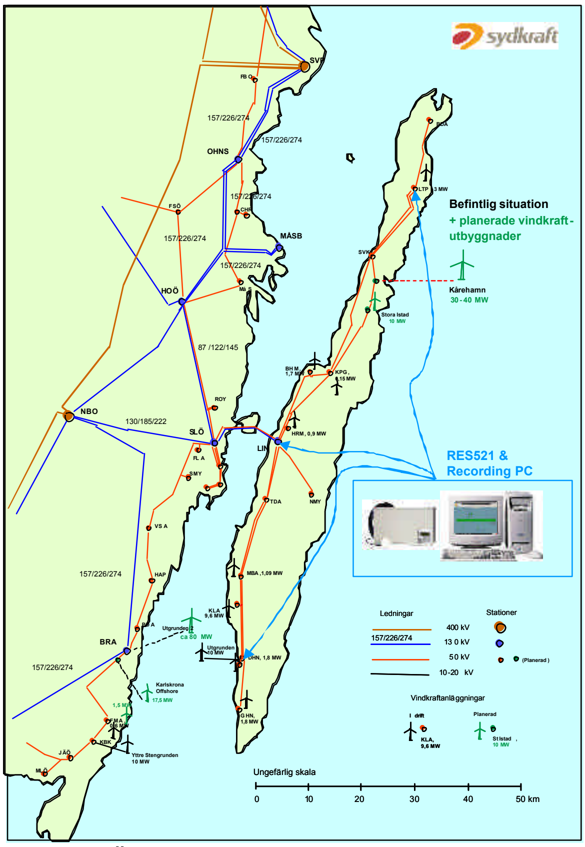

Figure 1-4 The test area of Öland, with wind power farms and recording nodes marked

In critical situations, whole areas are sometimes shut down to prevent the overall grid to collapse. Measurements during the black-out in Sweden in August 2003 showed that technologies and procedures used today sometimes worsen the situation. Automatic tap changers, for instance, focus on maintaining the voltage level of the distribution grid. They ignore that this action worsens the situation for the whole system if a concurrent voltage drop occurs in the transportation grid. EU research has produced an intelligent tap changer that takes into account the voltage level at the transmission level as well. Such a Critical Prevention Action solution is part of a wider strategy of distributed load shedding. Here, the action is not on the circuit breakers of the feeders, but on specific nodes inside them – a solution more flexible and effective in reaching the objective of balancing global production and consumption. Local agents evaluate the local load to shed and submit the required actions to their controlled loads and production units so as to meet the required local power variation. On top of this, forms of smooth load relief may be introduced via the agents managing the local cell.

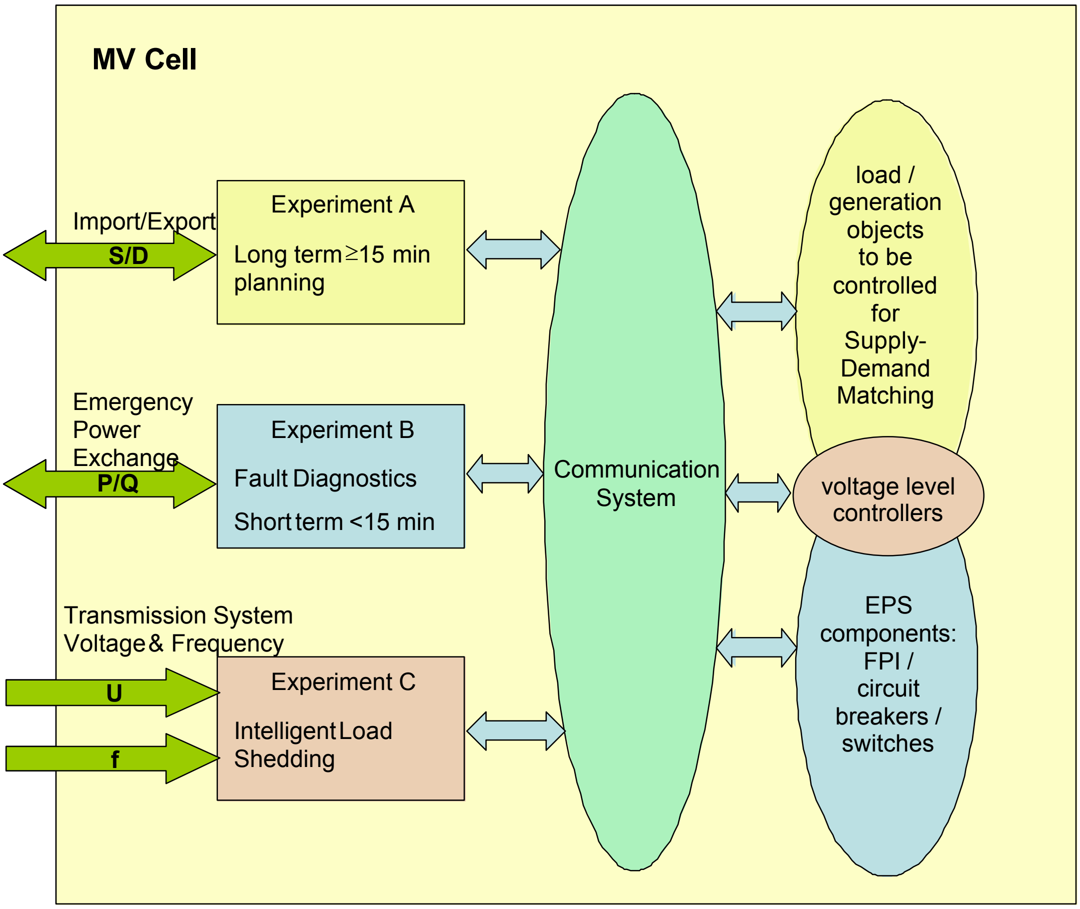

Figure 1-5 Relations between the WP3 experiments for MV cell design

Figure 1-5 shows the relations between the different experiments. Each experiment operates in its own time domain. However, they share a common ICT architecture in which they are implemented in a service oriented application environment.

2. Agents and Cells as new paradigms in the EPS control architecture

In this chapter novel concepts are described for operation of the power system. These concepts provide flexible solutions needed to face the challenges of massive introduction of DG and DG-RES. Intelligent operation of the power system will greatly enhance the value of DG and DG-RES by tuning supply and demand on all levels in the system. In critical situations DG will enable the keep the power system up at a local level.

In order to introduce intelligence to the grid traditional centralised and top-down control is no longer sufficient. Decisions will have to be made at the local level and will have to rely on highly automated control. The cell concept introduced in section 2.3 provides a flexible architecture for the power system that can adapt to disturbances in the system. Intelligent agents, representing these cells and having knowledge of its environment, can be scheduled to make decisions on the operation of the cells. Thus information can be kept at the local level, preventing large information streams to central control centres. Experiment B shows that state of the art ICT components can provide these solutions. More advanced protection systems also can provide smooth load relief using cell structured intelligent communication and control systems (Experiment C).

Agents also can provide solutions for tuning demand and supply in these flexible cells as has been demonstrated by the PowerMatcher concept implemented in Experiment A. In normal operation circumstances this market-oriented coordination system increases the value of local generation and relieves the pressure on line and substation capacity and on balancing capacity, thus avoiding large investment in system expansion. In critical situation operation local supply and demand matching is essential for cell operation.

2.1. Existing control solutions

Existing EPS operation involves complex systems of automatically or manually controlled loops where these numerous systems have different time responses and are interlinked. The existing structure is highly centralized: all data are sent to a central point for decision. The communication involved is used for different kinds of applications and associated time responses: power demand studies, energy and power trading studies, marketing, planning and designing large plants or heavy installations, scheduling the daily or weekly or monthly production expectations, responding to real time technical constraints, and so on.

The information exchange required in the EPS is generally bi-directional: need for remote supervision and control in the time are required for the application.

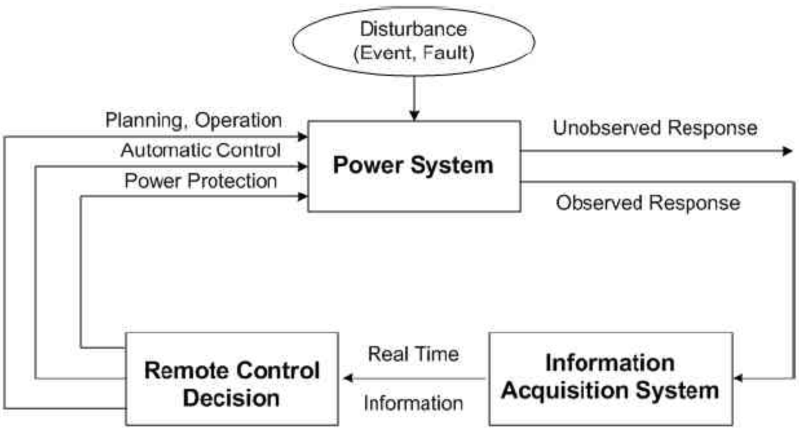

Figure 2-1 Simplified loop for EPS operation facing a disturbance

The transmission system is already provided with a wide and complex information system. It has been developed gradually along the last decades. Up to now, the monitoring and fast control of the distribution network (MV and LV) is weak, except for the cases where the energy involved and the need of power quality supply are high (as in main cities as New York, Paris for instance).

The existing real time monitored information system for the distribution EPS, is designed for protection and fast reaction to permanent faults. The monitored electrical parameters are, generally, currents and voltages in the substations (HV/MV level), the states of the circuit breakers, the states of feeder disconnectors and the states of some fault locators. The constraints of DG and local market actors will lead to a need for deeper monitoring of the network, ranging to the public MV and LV distribution system.

During an EPS emergency possibly leading to a blackout the distribution network, associated to actions on HV on-load tap-changers transformers, may contribute substantially to system stability. The technical solution already available may be to regulate the secondary voltages (tap-changers of VHV/HV transformers or HV/MV transformers) in order to maintain or decrease electrical current on the VHV lines.

Evaluation of existing control solutions

The main advantages of the existing control solutions are 1) that they are a relatively cheap way to control the contemporary Electrical Power System and 2) that they have more or less proven themselves over the past decades.[1]
The contemporary EPS is characterised by centralised generation in relatively few large power plants; a bi-directional transmission grid for interconnection of these large power plants with each other and with major load centres and major loads; and a distribution grid designed for a one way power flow from the transmission system towards the smaller loads. The current control solutions copy this hierarchical nature of the energy supply system to the control system, which is hierarchical in nature as well.

However the existing control solutions also have disadvantages, stemming from the limitations of the technology used:

- *lack of automation:* in the existing control solutions, lots of actions have to be done manually at physical locations in the grid. This means that applications like fault detection, restoration, reconfiguration and collection of load and energy information are *slower* than necessary because of travelling time, *more labour intensive* and done *less frequently;*

- *no specification of the result of control actions*: in the ripple control systems used nowadays for control of flexible loads no specification of the result of the action performed is possible, neither in advance (feed forward) nor afterwards (feedback). This means that an operator does not know the reaction of the system to his or her control action. This is like steering a car with the front window painted black;

- *static operation of the distribution grid*: with the existing control solutions large parts of the distribution grid are not operated in real time. Instead both the (re)configuration of the grid and settings and adjustments of protection systems are done manually. This means that the grid design, configuration and protection settings have to take into account the worst case situation of power flows. For grids with larger shares of distributed generation or flexible loads, this means that only negative and no positive effects of distributed generation and flexible loads are taken into account. This, in turn, causes over-sizing of the grid;

- *not suitable for incorporation of large numbers of distributed generators or flexible loads*: the incorporation of large numbers of distributed generators or flexible loads is not possible with the existing control technologies for several reasons:
  - the total number of generators and loads that can be controlled by a SCADA control system is limited because of the centralised nature of the SCADA system.
  - data management is also limited. Indeed, too much from DER and loads may flood classical Information Systems;
  - distributed generators or flexible loads can not contribute fully to the system stability and ancillary services even though they do take over part of the power generating function from central power plants;

[1] Even then, improvements of existing solutions are still possible, as was observed for the case of transformer tap-changer controllers (see section 2.4.3, conclusion 1).

- intentional islanding of parts of the grid is not possible with current autonomous protection systems. If it would be possible this could contribute to a higher quality of supply.

2.2. Software Agents

Agents represent a new type of Information Systems (IS) architecture particularly suited for distributed software applications as you have them in networked environments such as Intranets, Extranets and Internet/World Wide Web. Agents also offer several ways to embed intelligent systems techniques in large Information Systems. A description and overview of the characteristics of agents is given in Figure 2-2 below.

The control system being developed for the distributed generation network is characterised by linking software agents. These software agents are used for controlling these distribution grid cells, and distributed generators and flexible loads within these cells.

Figure 2-2 Definition and characteristics of software agents

Agents can be used as entities, which operate bottom up in conjunction with similar software entities to handle control complexity of operations such as the power grid. The modelling framework of autonomous agents with "knowledge" as defined in a limited number of operation rules can be shown to be superior to hierarchical top-down models[2]. The first reason for this is the maintenance aspect. Large top-down hierarchical networks can be shown to be difficult to maintain. Imagine in this respect, that configuration and data-tables of a network of tens of thousands of generators have to be maintained in a top-down manner. The second advantage has to do with easier hot-pluggability and authentication of agent-like actors in networks. Secondly, they are used as a modelling framework for distributed computation.
Multi-agent systems are also the underlying concept of the PowerMatcher (www.powermatcher.net), which combines agent theory with microeconomic principles, creating a coordination system for supply and demand of electricity in networks with a high share of distributed generation. Autonomously operating software agents, with their own responsibilities, are suitable to be used in scheduling power generation and consumption devices.

2.3. EPS Cells

The concept of MV level 1 cell and MV level 2 cell has been defined during the CRISP project. The historical and financial weight of the existing networks leads to assume that the physical topology of

[2] See Hans Akkermans, Jos Schreinemakers, Koen Kok - Emergence of Control in a Large-Scale Society of Economic Physical Agents. Proceedings AAMAS 2004.

the distribution network is relatively stable. The deregulation and introduction of massive DG and DG-RES will change the operation of the distribution system in a more flexible way: reconfiguration caused by real time power flow needs, new kind of load shedding or load reconnection system or load shaving, contribution to frequency control and reactive local compensation.

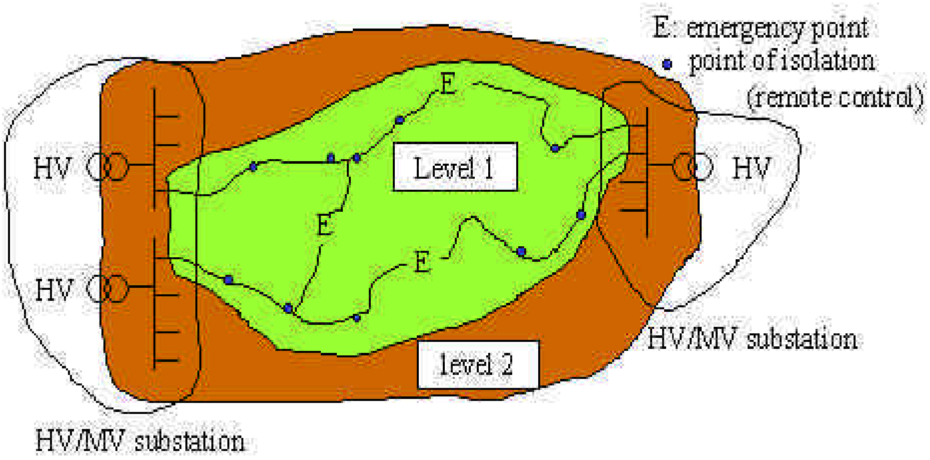

Figure 2-3 Level 1 and level 2 cell configuration

Two types of cells are defined joining one or several MV substations:

1. A network cell level 1 consists of a group of electrical components including conductors, DR and loads in one or several distribution network feeders (the different feeders are linked by normally open switches (E), as indicated in Figure 2-3). So, this cell level 1 is created by the concatenation of all the interconnected internal MV feeders. The boundaries of this cell are located at circuit breakers of MV substation. Each substation includes several cells level 1 in general.
2. All these cells level 1 can be interlinked through the MV busbar inside the MV substations and, so, generate a cell level 2. An illustration is given in the Figure 2-3 assuming that all the feeders are interlinked only between substation 1 and 2. The level 2 cell may be very large in urban system.

The definition takes into account technical constraints associated with existing distribution networks (the MV/LV substations play an essential role in the energy distribution and management at this voltage level). A simple view for the boundaries of the level 2 cell is the MV receiving-ends of MV substation busbar.

The cell concept refers not only to the EPS topology but also to the distributed part of intelligence associated: the cell has a function to achieve. Different missions may be assigned. The virtual utility defined through the MV level 1 cell or the MV level 2 cell could be operated by a local software agent. This software agent, as described in the previous subsection, is a concentrated node of information collecting data from all the internal devices of the cell. A part of the information should be analysed locally and should result in local decisions and actions (real time applications dedicated for EPS operation). Also this agent can exchange information with other agents, responsible for adjacent cells, and agents responsible for higher-level cells. Together, they could be able to decide how to reconfigure the grid after a fault, without overloading parts of adjacent or higher-level infrastructure.
When the cell includes a lot of applications (energy management, system support, autonomous control of voltage, flexible protection system, DR control, demand control), it could be then equipped in order to achieve the intentional islanding: this last and complex application must be seen as a possible future application.
This cell concept is general and will lead to a flexible MV network exploitation with DER insertion and variable production, a main point concerning the reconfiguration.

The MV cell concept is not new. It was already used at the beginning of electrification era. The difference today is the existing interconnected EPS, which is the main supplier for the distribution networks. Nevertheless already today a certain level of distributed intelligence exists in each HV/MV substation: for instance the protection system is able to take some local quick decision to open the circuit-breaker of a faulty feeder.

Evaluation

The new EPS architecture described here, consisting of distribution grid cells and a network of software agents, can help solve the problems of the existing control solutions in the following way:

- *remove the lack of automation:* with the architecture proposed, many applications that nowadays are done manually at the physical locations in the grid, could, in future, be done fully or partially automated. For example, applications like fault detection, restoration and reconfiguration were tested in experiment on *On-line Fault Diagnosis*. Applications like collection of load and energy information were tested in both in the experiment on *Supply Demand Matching* and in the experiment on *Intelligent Load Shedding*.

- *include a specification of the result of control actions*: from all three experiments, it is clear that the systems tested contribute to a better knowledge of the effect of control actions, both beforehand and afterwards;

- *from static to dynamic operation of the distribution grid*: experiment B *On-line Fault Diagnosis* was dedicated to dynamic operation of disconnectors/sectionalisers in the distribution grid and experiment A *Supply Demand Matching* to dynamic operation of distributed generators and flexible loads. Together they show - although still in an embryonic stage - the possibilities for dynamic operation of the distribution grid itself and the loads and generators connected to it;

- *remove barriers for the incorporation of large numbers of distributed generators or flexible loads*: by its very nature the architecture of distribution grid cells and interacting software agents is designed to enable the inclusion of large numbers of distributed generators and flexible loads.

The existing and new EPS architectures, including the concept of MV / LV distribution grid cells, are discussed more extensively in the CRISP report on Distributed Network Architectures [Deliverable D1.7].

2.4. Key overall findings on agent and cell architecture

The concept of MV level 1 and 2 cell is of a more general perspective than unique application to the localisation sequence as described in this experiment. The issue on ICT components used for fault detection and diagnosis have resonance with other applications as load flow management and supply demand matching in a same distribution EPS approach. Difference lies in the timing aspect of each application: Fault detection is oriented on operational issues and hence the timing process is crucial; less crucial are applications as intelligent load shedding, that need fast reaction from generation or from load in order to solve technical temporary issues. Supply-demand applications are valuable tools in normal operation of the network, ranging from long-term planning (hours and days) to balancing services in a 5-15 minutes ahead market.

The EPS cell concept leads to fast reconfiguration of cells. Flexible markets for rebalancing supply and demand in order to reduce peaks and decrease network losses can support these cells. In the eventual case of islanding intelligent load shedding and smooth load relief may be an essential part of a market based balancing solution.

Distributed ICT architectures combined with intelligent agents are indispensable fundaments in the control of large-scale dispersed generation in the grid. The very large increase of needed information exchanges involves adapting and developing the information system and network drastically. However, this can be done using state of the art ICT components as has been shown in the experiments.
The ICT developed and installed in the distribution network has to be based on low cost solutions, with performances adapted to the various function involved. A combined approach for different applications should be made. The ICT architecture should involve aspects as 'plug and play' and client-server models with thin clients.

2.4.1. Lessons learned

The experiments performed have clearly shown that new ICT devices such as described previously in the EPS are compliant. Already with the technology of today applications can be built that significantly contribute to a better operation even of today's distribution grids without DG.

As an illustration of the benefits of today's ICT, some of the benefits that can be derived merely from the applications studied in this CRISP project are listed:

- Imbalance Reduction within an electricity portfolio in the order of 40 % and peak reduction within an LV-cell in the order of 30 % by the application of SDM applications; this will also help to control local voltage decrease and to decrease network losses.
- Prevention of unnecessary voltage collapse in the EPS by the correction of improper tap changer behaviour;
- Reduction of outage time for customers not connected to the faulty section from 60 - 120 minutes to 45 seconds, by the application of an SGAD (Smart Grid Automation Device) for fault diagnosis and correction. (When a UPS is added, such outages can even be prevented completely for these customers.)

Just to be clear: even for the three applications studied in this CRISP project this list is not complete. Other applications can be thought of as well, each with their own additional benefits. (Such as intelligent metering, energy management and advice, this can lead to a better understanding of energy use and energy costs as well as a reduction of energy use.)

A general conclusion is that technology cannot be a limitation for further use of ICT to improve the operation of the distribution grid: the basic technology is available.
Major bottlenecks are nowadays development of proper applications, standards and regulations. When these have been developed, business models will become available as well. Also it is important that industry gets to recognize the opportunities of ICT in the Electrical Power System.

In a grid with a high number of DG units, the huge number of units to be controlled might be a problem. In a large transmission grid this number could go up to tens or hundreds of millions.[3] For traditional SCADA control systems, this number of control points will definitely become a problem. However for this there is a solution: When we leave the SCADA paradigm of centralised and top-down control and use real time agent applications in the EPS as described above, control is based on bottom-up and horizontal communication and control from various (coordinated) decentralised control points. Then it is not necessary to gather all information about the whole grid on one central control point.
Both the ECN field experiment on Supply-Demand Matching and the IDEA tests of the SGAD for Fault Diagnosis make clear that real time agent applications in the EPS pre-eminently are feasible and provide scalable solutions. An important aspect of this solution is that cells should be as autonomous as possible, with each software agent responsible for its own area of control.

Another general conclusion from the experiments is that it is both needed and possible that the system provides ancillary services for the DG units and that the DG units provide ancillary services for the system. The measurements on Öland have made this clear, showing that current conventional wind farms trip in reaction to grid disturbances at a distance of hundreds of kilometres.

Combining multi-agent systems with microeconomic principles
The tests at ECN show that agents representing generating and consuming devices and acting on an electronic power market can provide a stable coordination system for supply and demand. Handling both, price formation in distributed markets and time-scheduling of loads and generated power is feasible. Time scheduling of 5-15 minutes can be reached. The tree-structured approach of the PowerMatcher and the used agent algorithms make the PowerMatcher also a highly scalable solution. The commercial scenario for integration of intermittent resources such as wind power may provide a good case study for commercialisation of the application. Imbalance reduction of 40% by making use of flexible demand is of high value. Adding more flexible supply may improve this figure.
Although Experiment A has been implemented in a commercial scenario without direct grid-coupling, we can derive some conclusions for utilising the PowerMatcher at the cell level. The simulations in a

[3] Depending on technological, environmental and energy market developments every household might have one or more DG units like micro-CHP-generators or small scale wind turbines by 2020 or earlier! In a later stage also PhotoVoltaic generators might see an increased market penetration.

grid-connected environment in the LV-cell scenario show large peak reductions in the order of 30% and a smoother load over time. Further research may be aimed at a closer connection between the grid and the PowerMatcher. Technical parameters in the electricity network can provide input to local stability control, such as: capacity constraints; dips and surges; voltage level and frequency; ancillary services etc. The time scale from operation to control is essential here. Some control aspects will have to be solved locally at the node, others may provide input for valuation in the optimisation process of the PowerMatcher.

SGAD for online fault diagnosis tests
The IDEA tests with an SGAD for Online Fault Diagnosis show that the MV Cell approach for EPS and ICT works. With this cell approach, it is feasible to increase the level of grid automation and thereby to reduce the interruption time for MV faults for clients not connected to the faulty grid section itself from 60 to 120 minutes to 45 seconds. If one uses a UPS in addition to this, either at the customer side or somewhere in the grid, one can avoid even these short interruptions.

Next steps in the development of such applications are the test of the interaction of several agents. Indeed, to maximize their performances, some few communication interactions should be added in order to take into account their mutual effects on each other. The Help Tool for Fault Detection (HTFD) could also be used to find steady state configuration that minimize the losses or maximize the viability of the EPS for instance (like Distribution Management Systems having strong and fast HTFD capacities). The idea of such studies could be the benefit evaluation of the reconfiguration versus the lifetime of the switches.

Intelligent Load Shedding field measurements
These measurements show that current state-of-the-art protection systems are not optimal, even without large shares of DG. They also show that distributed generation can have a positive impact on the power system stability, but the design and control systems have to be chosen carefully.
From the CRISP analysis of the Swedish blackout 2003-09-23, it was learnt that the voltage levels in the transmission system are good indicators to identify transmission capacity problems, and enough time is available to take counter actions, such as load shedding. Our conclusion is that voltage levels are good candidates to identify voltage instability problems and can be used to initiate load shedding.
The consequences of large power system disturbances can be significantly reduced by the use of “intelligent load shedding” – i.e. smooth load relief achieved by cell structured intelligent communication and control systems, to keep track on load objects suitable to shed, and intelligent methods to identify the power system conditions, to decide where, when and how much load to shed, to save the power system integrity in a critical situation. In this way load shedding can be much improved. In fact, if managed properly it would be better to change the concept of 'load shedding' towards 'load control'.

2.5. Recommendations for future research

Still a lot of aspects of a future smart electricity network with a large share of DG remain uncertain. Therefore a lot of research is needed, including the following topics:

- better supply and demand prediction (essential for balancing the electricity system)
- advanced applications for the PowerMatcher, aiming at a controlled exchange between an EPS cell and its environment (rather than at a balance at a cell level).
- advanced applications for load control, to improve the stability of the electricity grid;
- advanced applications for online fault diagnosis and recovery, to improve the reliability of electricity supply without major investments;
- Intelligent decision support for risk and security analysis of distributed generation networks that not only includes maximum availability considerations but also integrates economic cost-benefit and priority analysis on an equal footing;
- other ICT applications to improve the operation of the electrical power grid.

In general, a number of well-documented, common reference cases within and among European research projects should be established to share the same use cases and build a common library.
Sharing such a common technical set of data will help to disseminate general and detailed information between the different involved experts, from power systems, markets or ICT. A lot of assumptions are taken into account in the EPS models and simulations. Combining aspects of EPS, markets and ICT lead huge efforts to set possible realistic benchmark. Improving and accumulating common database

will be profitable for the various European experts for defining the technical problems (illustrative cases), for disseminating the main results of specific proposed solutions. Afterwards the comparisons between concepts or solutions will remain relevant because based on similar cases.
A real experimentation should involve large expenses if done at a scale of a MV cell. Such an experimental site may be used for various European projects around the issues of DG insertion into the EPS.

3. State of the art ICT

One of the main aspects of the experiments has been to demonstrate that advanced applications in a highly distributed power network can be carried out using state of the art ICT. This not only requires development and use of state of the art ICT components, but also needs investigation on whether various ICT requirements are met.

3.1. Existing ICT in power grids

In the MV network, grid owners presently use ICT to monitor and control remote MV-stations and disconnectors. In the public LV networks, a main application being developed by utilities is AMR (automatic meter reading). The principal role of AMR is to measure the electricity consumption of low voltage customers, e.g. in a monthly period. The current results for this application are good in terms of reliability of the system: nearly 99% of availability. Since for current applications the information is nearly 15 bytes coded, there is no high constraint in local memory storage and in data transmission.

The communication can be exchanged via different technologies of which some are listed below with pros and cons:

- Dial-up connection through a hard-line or a wireless connection such as GSM, 3G, satellite phone:
    - Three mains stages: taking connection, checking identification, transmitting data
    - Taking connection is time consuming, nearly 30 s
    - Identification and data transmission depend on the rate flow existing, these stage may be very fast (a few ms in the best cases to a few hundreds of ms)
    - It is sensitive to weather (except for the satellite phone) and power outages
    - It is relatively cheap to install.
    - Especially the hard-line has a low reliability due to accidental or weather related faults on the wire.
    - Reserving and keeping connection may be expensive but offers a fast communication solution

- Radio waves – either a direct link or transmitted via slave transmitters in other stations or radio towers.
    - Often used for disconnectors located out in the MV grid and smaller MV stations due to the lack of accessibility for other technologies.
    - Communication via a direct link can be disabled in still sunny weather, due to the layering of the air under these conditions.
    - The typical flow data rates observed in utilities may be no more than 600-1200 baud, depending on the targeted application (example of automatic meter reading).

- Ripple control
    - One way communication (top-down only), with low communication speed
    - Uses the power infrastructure itself and covers the whole infrastructure (where not disturbed)
    - Very low reliability: sensitive for interference and Power Quality problems, no confirmation of receipt of message.
    - Used for applications like switching of tariffs, switching of public lighting and classical (centrally controlled) Peak Shaving schemes.

- Fibre optic cables.
    - Expensive high-end technology used for VHV- and important HV stations.
    - Very fast communication capabilities in this medium

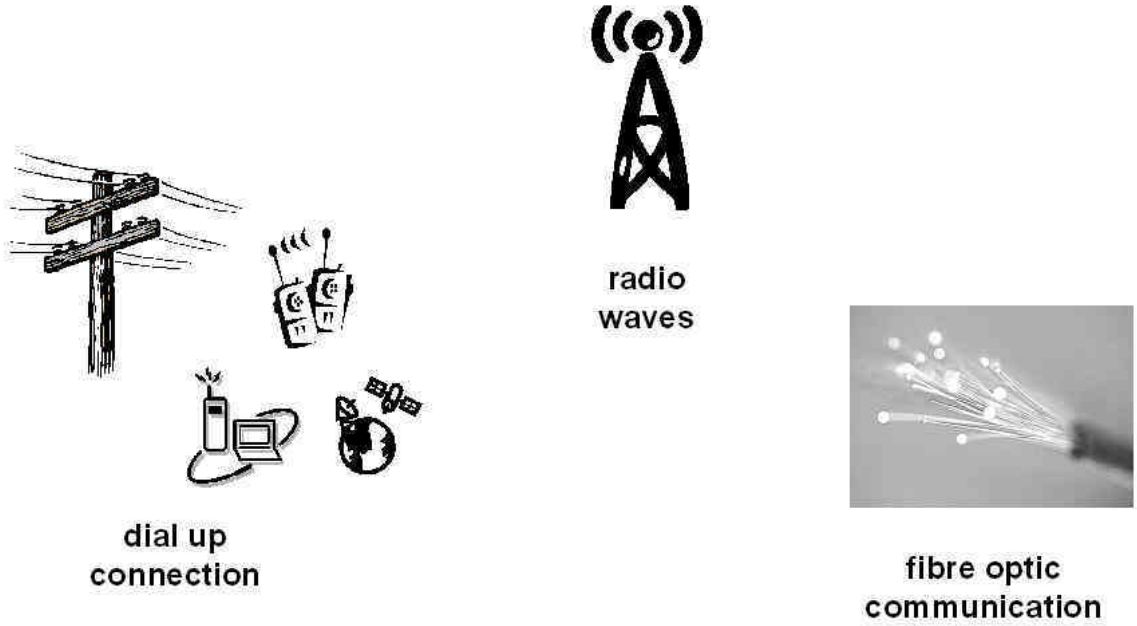

Figure 3-1 Various types of communication available for automation of the power grid

The line of communication between a remote controlled device and the central SCADA system often is a mix of the above-mentioned technologies. Radio or PLC may be used as communication support between the customer and intermediate communication node (for instance installed near a MV/LV transformer). Then between this intermediate node and the central control room, technologies as GSM/GPRS/Radio/ADSL may be used. Even if the price today is high for these relatively new technologies (GSM, GPRS), it is decreasing nowadays with the increase of the associated market.

Challenges for ICT in power grids
Various, contrasting developments put the future operation of power grids under tension:

- liberalisation of the electricity markets, resulting in increasing demand for flexibility
- decreasing possibilities for central control of supply and demand balance, because of increasing penetration of DG and RES
- growing need for ancillary services at the distribution network level (like voltage and Power Quality control), because of increasing penetration of DG and RES
- increasing requirements on grid reliability and power quality, due to the growing reliability of society and economy on the power supply
- goals of regulators to decrease the total cost of ownership
- goals of grid owners to increase their return on investment

More ICT in the grid makes it possible to utilize the grid more as more information and control makes it possible to push the transfer limits.

3.2. Key overall findings on ICT requirements

3.2.1. Local autonomy

In the classical SCADA-architecture of EPS control systems all decisions are taken at the top level of the system - except for a few pre-defined actions in case of failures or emergencies. Instead, in an ICT architecture based on distributed intelligence, local agents can operate autonomously. Each agent takes care of a single end device (e.g. a consuming or producing device or a grid component) or a group of devices (e.g. a commercial cluster or a grid cell) and can decide to send commands to other devices or to a group of devices. The experiments are designed to prove the technical feasibility of this concept of local autonomy.

The experiments performed show that local autonomy is feasible and agent systems are a good paradigm to guarantee this autonomy. Agent systems also have the advantage that the amount of communication towards a central supervisory system is drastically reduced.

In the ECN field experiment on Supply-Demand Matching local PowerMatcher agents control all devices. They determine both the predicted programs and express their real-time requirements by bids. This leads to different control (as can be seen in Figure 3-3 and Figure 3-4) than conventional, but by no means inferior control. In the Experiment A control has only been exercised in the residential dwelling. Technical disturbances several times led to failure of the system, leading to unacceptably low temperatures in the dwelling. As a lesson in a follow-up project a backup control has been implemented: whenever the market fails, conventional backup control takes over. Local intervention is also necessary if local conditions are not satisfied such as out-of-bandwidth- temperatures, or because of user requirements.

The simulations on a SGAD device for Online Fault Diagnosis show that agents for Online Fault Diagnosis can detect and correct a grid fault within 45 seconds, without any need for communication with a central SCADA system. This means that - in principle - an autonomous agent for Online Fault Diagnosis and Restoration can be introduced into the grid. This will drastically reduce the interruption time for MV faults for the clients not connected to the faulty grid section. Before the SGAD devices can really be introduced into the grid, it is necessary to develop prototypes and corroborate the simulation results with field tests.

In the ABB / E.On / EnerSearch field measurements on Intelligent Load Shedding it was found that the voltage levels in the transmission system are good indicators to identify transmission capacity problems. This means that an autonomous agent could be designed that decides on load shedding actions on the basis of voltage level measurements. This agent should have the capacity to learn about the interaction between load, distributed generation and the power system. Also for this application, it is still necessary to develop prototypes and corroborate the results with field tests.

3.2.2. Horizontal / vertical communication; top-down versus bottom-up communication

In the traditional SCADA-architecture all communication is top-down, between the central SCADA-system and the grid devices. Horizontal communication between neighbouring grid devices is not possible. In the alternative ICT infrastructure that has been investigated in the CRISP project a mixture of horizontal and vertical communication is presupposed. All agents can still communicate vertically (downwards to components of their group or upwards to overlying group agents). In addition to this they can also communicate horizontally, with peer agents (e.g. a neighbouring grid cell). One of the questions to be asked is whether or not this mixture of vertical and horizontal communication can work.

In the experiments as they were performed horizontal communication as such did not play an important role. Important was that the vertical communication could be limited to one step upwards, towards a clustering agent. That clustering agent decided autonomously, with only limited communication further upwards towards a central control system.

In future applications these clustering agents might not only communicate vertically with 'their' assigned lower level agents.[4] They could as well communicate horizontally with neighbouring clustering agents. At this stage, this was not explicitly tested in the experiments, but no reason has been found from the test results why this would not work. On the contrary, on the basis of the experiments, the expectations are that horizontal communication between clustering agents would strengthen the local control capacities of the system and further reduce the need for communication with a central control system.
A whole range of simulations and experiments is possible to corroborate these expectations. It is recommended to pay special attention towards characteristics of the distributed control system like reaction speed, required communication capacities and system stability.

[4] These lower level agents could be either end device agents or clustering agents of a lower level cluster.

3.2.3. Communication speed an other timing aspects

One of the prerequisites for controlling a flexible EPS with a large share of distributed generation is that sufficient data communication is available. Using distributed intelligence with local autonomy and horizontal communication already reduces the amount of communication needed. Still a question remains about the communication speed needed. Two relevant quantities are the effective baud rate (number of useful data transmitted per unit time, in bit/s) and the latency (maximum delay of data packages before arriving, in ms).

Minimum required communication speed depends on the type application. Especially in the French tests with a SGAD for Online Fault Diagnosis the effect of the communication speed on the overall performance of the SGAD system were measured.

Communication Link	Delay (ms)
Fibre-optic cables	100 - 150
Digital microwave links	100 - 150
Power lines (PLC)	150 - 350
Telephone lines	200 - 300
Satellite link	500 - 700

Table 3-1 Latency of different communication media

While communication speed is essential for the fault detection experiment B, the PowerMatcher experiment A is less dependent on communication speed. Communication through ADSL and UMTS did not lead to any performance or congestion problems. Programs, bids and allocations are communicated through short messages. Failure in the system, such as communication loss and malfunction of components, can also disturb the market and/or local operation. It requires at the central node robust algorithms, although not every failure can be counteracted if no information is available about the reason of failure. For the experimental cluster market rounds of 15 minutes did not pose any problem. Even higher frequency markets (up to 1-2 minutes) should be feasible. For larger clusters with several scores of devices parallel communication through separate threads will be necessary.
Special attention should be paid to time synchronisation between the different local nodes in order to enable each node to participate on the market on time. This should not pose any problem if market initiative is left to the aggregation node.

3.2.4. Scalability

To control an EPS with large numbers of distributed generation units a crucial prerequisite for a good solution is that it is scalable. This means that it can be enlarged according to the needs, without damaging the functionality. In the end stage of the integration of DG, the EPS control system should be able to control hundreds of millions of DG units across the European power grid and around ten times more flexible power consuming devices.[5]

Scalable solutions are feasible with real time agent applications. The PowerMatcher concept, as has been used in the supply-demand matching experiment, is highly scalable by use of aggregating nodes (see Figure 3-2). These aggregating nodes mimic logical EPS components: in grid-coupled control one might think of in-house connection points and LV-MV substations as logical aggregation nodes. Moreover, the agent approach and the tree-based market algorithm support this scalability and ensure a guaranteed market outcome.

Another aspect of PowerMatcher scalability is the number of nodes that can be aggregated into one single PowerMatcher node. The PowerMatcher is built according to the web-services model. Intelligence is built into the lower level agents, communication is based on simple messages, and the central PowerMatcher algorithm is highly scalable by nature because of its underlying tree-structure. This leads to a first indication that the PowerMatcher concept also is highly scalable in this aspect. However, communication infrastructures (UMTS, GPRS) might be a bottleneck. Load and stress tests may be applied in future to find out how the PowerMatcher scales as the number of clients increases.

[5] The number of people living in the 25 EU member states currently is around 450 million. It is projected that eventually each household can have one to five DG units and around ten flexible power consuming devices.

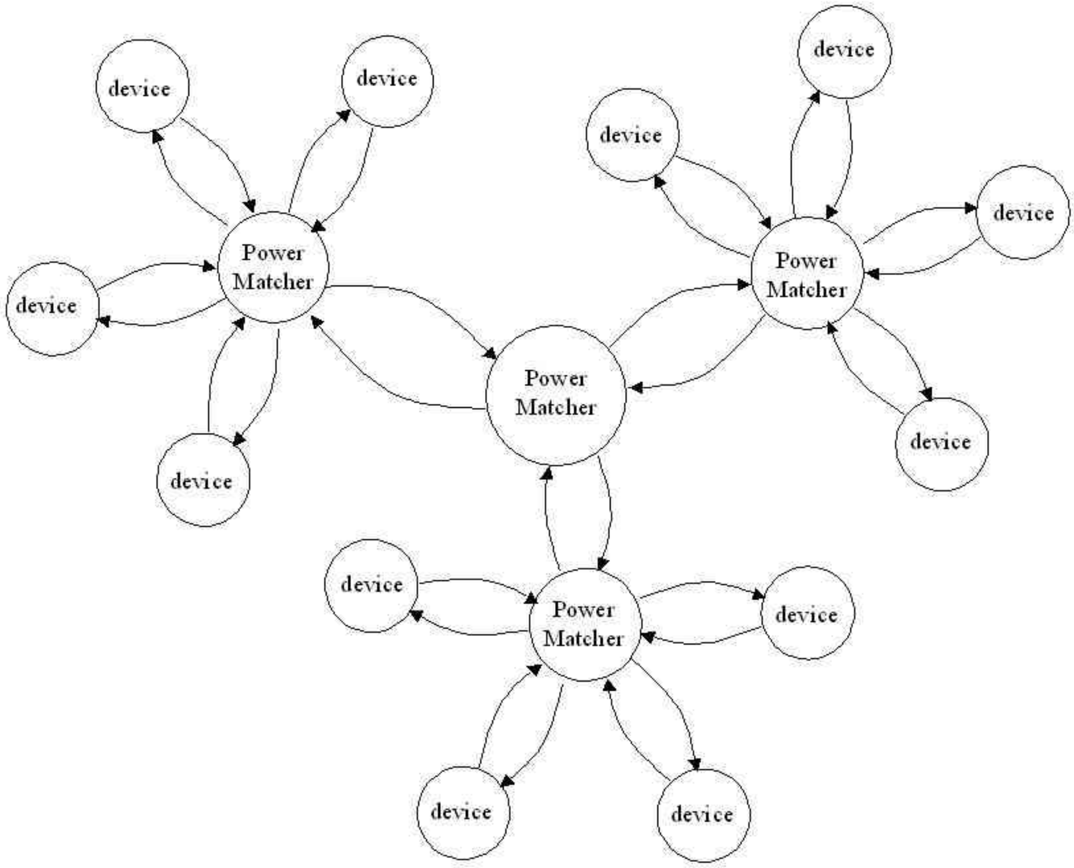

Figure 3-2 PowerMatcher scalability by node aggregation. Each node interface consists of bids (from lower level to upper level) and prices (vice-versa).

3.2.5. ICT Components

The network for the fault experiment B was built using standard computers and Ethernet links, a simple TCP-based communication protocol, dedicated traffic shapers, and the Arene real-time network simulator. The use of a simple and standard communication protocol allowed determination of realistic minimal overhead when transmitting fault data from different stations. Communication tests have been done with an elementary cell composed of two interconnected medium voltage feeders, always assuming open loop operation as used today by utilities.

The imbalance reduction experiment A was built using off-the-shelf computing and communication hardware. They have been used to interconnect and interface the cluster of power generation and consumption installations in a network using secure Internet-technology in an isolated branch of the public Internet, a virtual private network. On these computers, tools have been installed for data-collection, database storage and safe execution of novel control algorithms.

On-site connection to existing energy management systems has been made according to the design layout. The OPC-Server proved to be a good mechanism to get access to local installation data.
The CRISP tests demonstrate the value of TCP/IP dedicated communication boxes and programs set up in a modular way. A next step forward is to develop a low cost solution that is easy to install, easy to configure, and easy to maintain. Generally, the grid cell architecture with associated SGAD agent systems gives a concrete outline of a standardized approach to distribution automation for future electrical power systems.

3.2.6. Particular findings from the experiments on ICT requirements

Supply Demand Matching System Field Experiment
In the ECN field experiment on Supply-Demand Matching local PowerMatcher agents control a real heat pump in a house. The agents make their control decisions autonomously on the basis of information they received from other PowerMatcher agents. The PowerMatcher agents on one hand

offer their flexibility on the portfolio imbalance market; and on the other hand secure that their devices are operated within the limits set in advance. Figure 3-3 and Figure 3-4 show the difference in strategy between conventional control of the boiler, having the shape of a saw-tooth, and the PowerMatcher control, shaped on the market outcome. While the first recovers after each usage dip to a temperature of 50 °C, the PowerMatcher uses a temperature band between 40 °C and 55 °C.

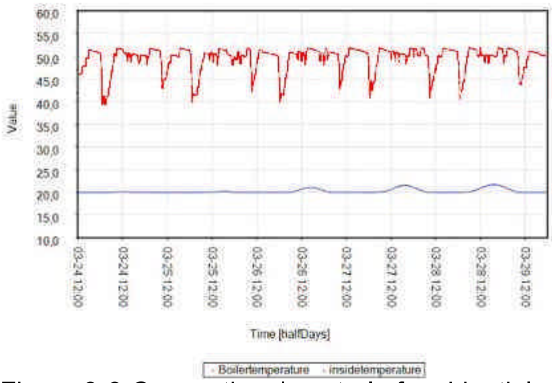

Figure 3-3 Conventional control of residential dwelling: boiler and room temperature

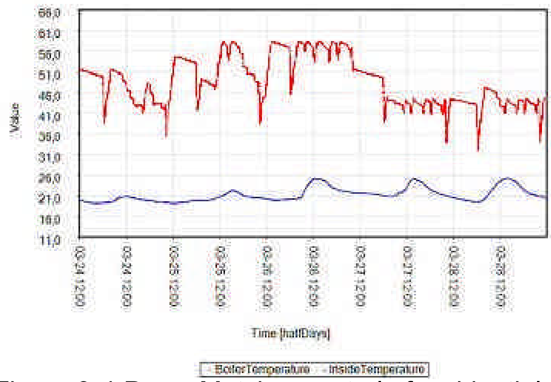

Figure 3-4 PowerMatcher control of residential dwelling: boiler and room temperature

SGAD for Online Fault Diagnosis
During disturbances in the power grid abnormally large amounts of signals are sent from the grid to the SCADA-system creating bottlenecks in different parts of the ICT-system when communication with RTU's. To avoid this issue the communication could be controlled by an IP protocol, for instance IEC-870-5-101. In this new protocol signals may have different importances, different priorities. Hence during a large disturbance the important signals should not be delayed in bottlenecks as the situation could be today. A further advantage of implementing signal priorities is that the operators, during a disturbance, could chose only to have the most important signals displayed on their screens, making it easier for them to stay on top of the situation.

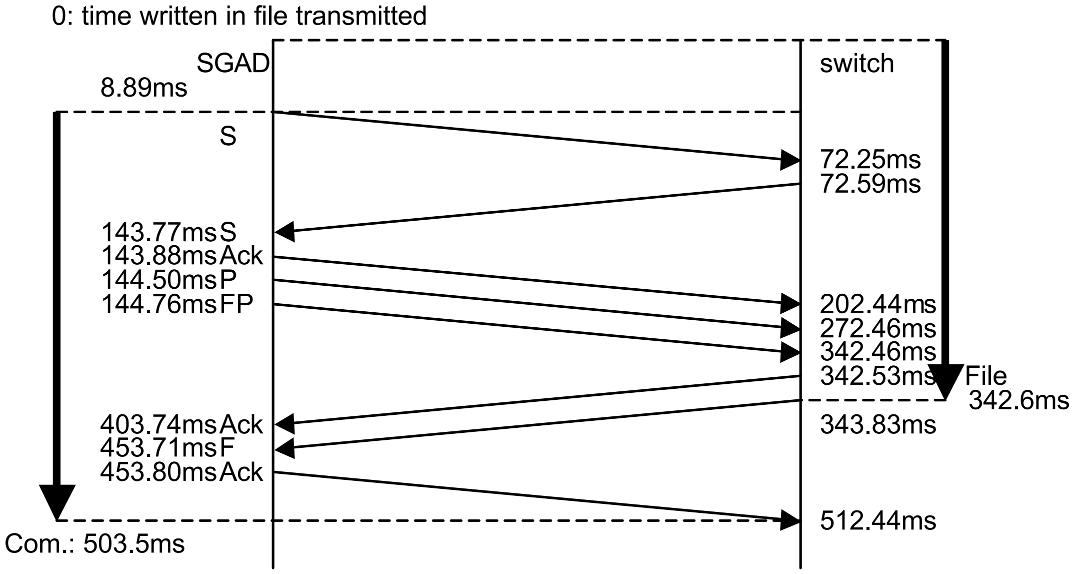

Figure 3-5 Link from SGAD device to Switch device with simulated radio link

So two aspects have to be considered on the reception of information in a control centre in case of critical situation involving fast and adequate responses:

- The human being in the control room has to take decisions. He has physiological limitations and need a selected set of data. So the transmitted information may be sized and prepared in this way for fast operator reaction: this involves specification for distributed intelligence and for priority in the local communications.

- The control centre may be equipped for automated fast responses, but also has limitations in its communication inputs capacities, some bottlenecks could delay important income messages. A priority in the communication process has to be managed in this way too.

This would enhance the probability to be able to maintain the ability to monitor and control the MV parts of a power system during large disturbances.

3.3. Recommendations for future research

A next step forward is to develop a low cost solution that is easy to install, easy to configure, and easy to maintain. Especially the device agents should be implemented in a service-oriented architecture with special attention to communication with its local environment. One way to achieve this is by integration with solutions such as the Zigbee initiative that provide reliable, cost-effective, low-power, wirelessly networked, monitoring and control.

Agent technology, using algorithms from micro-economic market theory for massive coordination, offers a scalable mechanism that manages the complexity of price formation and supply-demand matching in fine-grained bottom-up control distribution networks. A further implication for market and business models, however, is that current commercial approaches for pricing and contracting must be updated as well to benefit from this technological progress.

The SGAD devices are developed and tested in a controlled simulation environment. Before they can really be introduced into the grid, it is necessary to develop prototypes and corroborate the simulation results with field tests.

Autonomous agents could be designed that decides on load shedding actions on the basis of voltage level measurements. These agents should have the capacity to learn about the interaction between load, distributed generation and the power system. Also for this application, it is still necessary to develop prototypes and corroborate the results with field tests.

On the basis of the experiments, the expectations are that horizontal communication between clustering agents would strengthen the local control capacities of the system and further reduce the need for communication with a central control system. A whole range of simulations and experiments is possible to corroborate these expectations. It is recommended to pay special attention towards characteristics of the distributed control system like reaction speed, required communication capacities and system stability.

4. Dependability and security

Future cell-structured EPS and virtual power plants (VPP) based on distributed energy resources are to be designed for dependability, security, and adaptivity. In fact, the future grid architectures consist of the energy system coupled to embedded information systems, so that we have to deal with the interdependencies between two critical infrastructures. Simultaneous protection of critical EPS infrastructures and of critical information infrastructures is therefore a major concern.

Basic services that ICT systems must provide in a dependable and secure way are:

- Support of the EPS management tasks.
- Meeting prescribed performance criteria.
- Support observations and maintenance of the integrated ICT-power systems.
- Support reconfiguration and restoration of the EPS network as well as of the ICT network.

4.1. Classical SCADA

For the future networks, the classical SCADA systems will not be able to do so. They have a vertical hierarchical architecture that, indeed, closely mirrors the hierarchical structure of the classical power grid. This rigidity is a major drawback in view of the emerging distributed power networks that have to be managed in a less top-down way. Growing EPS complexity and interdependency make the classical information systems increasingly vulnerable, as we have witnessed for SCADA systems in recent blackouts.

4.2. Emerging standards

The bottom line, then, is: we have to replace today's vertical, closed and hierarchical SCADA systems by more flexible, service-oriented information systems. Functionalities within current SCADA systems have to be decoupled and redesigned as bundles of services that can be configured horizontally as well as in the classical vertical manner.

To achieve such goals, new information systems architectures have recently emerged in ICT that are known as Service Oriented Architecture (SOA). The top layer is typically based on Web Service standards; the middle layer is strongly based upon Internet-related standards such as TCP/IP protocols; the bottom layer is based upon standards below the network (IP) layer, which are commonly industry- and device-specific.

A development that practically supports the move towards decoupling of SCADA functionalities and more flexible service-oriented ICT support, are emerging IEC standards (http://www.wg14.com/), such as IEC 61850, 61968 and 61970. Those standards could moreover support the development of dependable and secure ICT systems more than those built on Internet standards alone.

4.3. Key overall findings on Dependability and Security

Performance

A Service Oriented Architecture has been successfully used to support the various CRISP applications and tests, especially Experiment B on fault detection. For example, it underlies the CRISP network configuration and visualization support toolbox that we have used to test ICT performance (delay and throughput) in the CRISP experiment B on fault handling. This is illustrated in Figure 4-1.

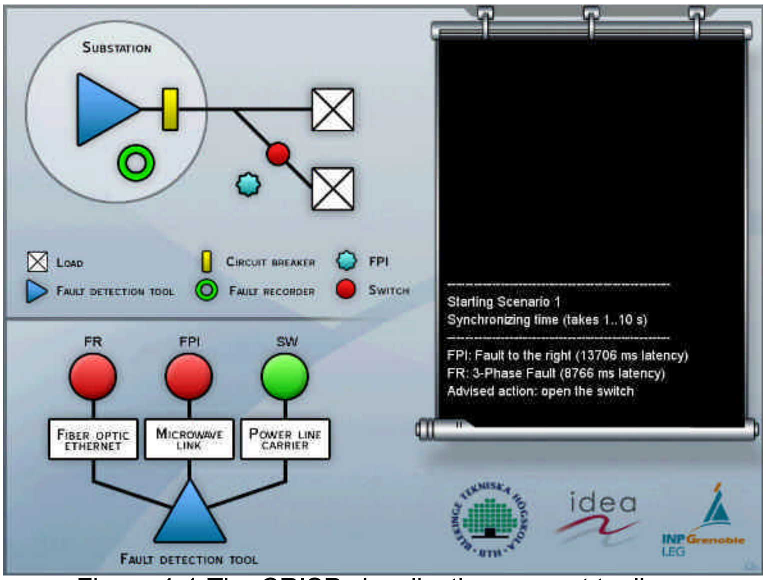

Figure 4-1 The CRISP visualization support toolbox.

These experiments show that real-time performance of ICT networks to help protect the grid can be achieved by properly configuring the embedded ICT. Some lessons learned here are:

1. An open Service Oriented Architecture is valuable to assess and satisfy ICT criteria related to dependable operations of future EPS. The open architecture allows one to experiment with different protocols and their performance.
2. Trade-offs exists concerning time and speed between doing local computations (by individual agents themselves) and sending information messages (between communicating agents). These trade-offs are of help in alternative system designs to achieve required real-time performance criteria.
3. By utilizing free bits in the IP protocol we can prioritize the routing of packages to meet real-time constraints.

The toolbox and test-bed displayed in Figure 4-1 have also been used to validate mechanisms for protecting execution. By tailoring routing algorithms we have validated that we can protect (detect, localize, and restore) the power grid even in time-critical situations.

Robustness
From Experiment A the following conclusions can be drawn on the robustness of ICT:
Failure in the system, such as communication loss and malfunction of components can disturb the market and/or local operation. It requires at the central node robust algorithms, although not every failure can be counteracted if no information is available about the reason of failure. For example, if the wind turbine cannot make a bid, it is unknown whether the turbine has been shut down, or it is still operation.
On the other hand it also requires a fallback scenario for the local installations. This can be made part of the local autonomy of each installation. In the field test this has not been an issue of study. In some periods, due to system failure, the temperature in the residential building has fallen far below acceptable values. In a follow-up project this has been made part of the local strategy. The installation disconnects and switches to conventional control, when temperatures drop below acceptable a threshold.

4.4. Recommendations for future research

The CRISP experiments involve (technical) power grid protection as well as (higher-level) business processes such as balancing services. Consequently, the mechanisms for security and dependability must be able to work both at the level of technical grid operations and the level of supplier-customer business processes. The ideal situation would be that the same framework for dependability and security applies to both levels. This is clearly one of the challenges ahead.

However, the CRISP project has produced some useful insights that indicate how one can make further progress in this area. First, it appears that Service Oriented Architectures are useful as a foundation both for technical operations such as fault detection and grid protection, and for higher-level business services such as commercial supply-demand matching. So, these very different applications can be modelled on the same service oriented platform.

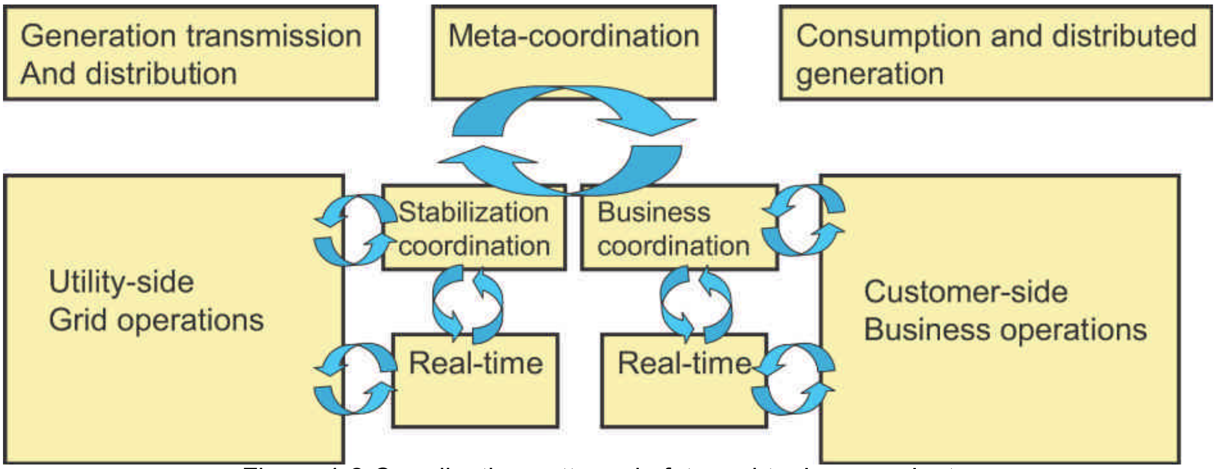

Figure 4-2 Coordination patterns in future virtual power plants.

A next step, then, is to define a common business model that integrates and coordinates the grid protection and the business services on top of it. In terms of the visualization of Figure 4-1, such a common business model would allow to buy or sell power from an EPS node within a cell (in a “yellow” state), so as to prevent a critical “red” situation (load shedding or blackout), and bring the grid back to a “green” state. Such an integrating secure business model for future virtual plants has to contain a range of coordination patterns (Figure 4-2).

5. Conclusions

Fault detection and reconfiguration is one of the operations that can be automated in a cell-based grid architecture. The CRISP project has therefore developed a Help Tool for Fault Diagnosis (HTFD) in EPS, with a modular and configurable experimental test-bed for ICT network performance measurements.

Cell-based architectures with smart grid automation devices are a basis for future distribution automation.

Agents, electronic markets, and service-oriented architectures are the ICT means to make the grid intelligent and self-organizing.

Field experiments with automated electronic markets show significant power imbalance reductions. This is also supported by simulation studies in which local electronic markets reduce peak power import and decrease fluctuations.

Under-voltage is a good grid stability indicator in critical situations. Great improvements are possible with simple means, among them intelligent on-load tap changer control.

Efficient ICT communication in electrical power systems is possible with the IP Internet protocol; special mechanisms for secure execution provide protection.

5.1.1. Industrial guidelines and recommendations

The experiments have shown that several ICT applications in the distribution grid each have their own benefits. They also have their own requirements on issues like ICT infrastructure, communication and market design. However a lot of requirements are common or can be reconciled, if done in the earliest stages of development. Therefore to really reap the fruits for distributed intelligence in the EPS, a common ICT system should be developed. It could support several applications that run in parallel. Service-Oriented Architectures (SOA) can provide such an infrastructure.

In addition to this, a standard market design including a communication standard should be developed to support the smart electricity grid applications.

On all these fields, simple, flexible, standardised solutions should be chosen that are error-proof, easy to install and maintain and easily extendible for future applications.

A consequence of large scale introduction of DG is also that new guidelines should be developed for DNO's and for DG equipment. New guidelines for DNO's should include topics such as Quality of Supply and Power Quality with distributed generation in the MV and LV network. For instance the EN50160 European standard for quality of supply may be adapted with this new control features on production and loads. New guidelines for DG equipment should take into account the role that DG has to play in maintaining the system.

Acronyms and abbreviations

Acronym	Means
ADSL	Asynchronous Digital Subscriber Lines
AMR	Automated Meter Reading
CHP	Combined Heat Power
CRISP	Distributed Intelligence in CRitical Infrastructures for Sustainable Power
DER	Distributed Energy Resources
DG	Distributed Generation
DNO	Distribution Network Operator
EPS	Electrical Power System
GPRS	General Packet Radio Services
GSM	Global System for Mobile Communications
HTFD	Help Tool for Fault Detection
ICT	Information and Communication Technology
IEC	International Engineering Consortium
IS	Information System
(LS)VPP	(Large Scale) Virtual Power Plant
LV	Low Voltage
MV	Middle Voltage
OPC	OLE (Object Linking and Embedding) for Process Control
PLC	Power Line Carrier
RES	Renewable Energy Systems
RTU	Remote Terminal Unit
SCADA	Supervisory Control And Data Acquisition
SDM	Supply and Demand Matching
SGAD	Smart Grid Automation Device
SOA	Service Oriented Architecture
TCP/IP	Transport Control Protocol / Internet Protocol
TSO	Transmission System Operator
UMTS	Universal Mobile Telecommunications System
UPS	Uninterruptible Power Supply
(V)HV	(Very) High Voltage