Distributed Intelligence in Critical Infrastructures for Sustainable Power
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Final Summary Report

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Table of Contents

List of Figures

List of Tables

Executive summary

How will Information and Communication Technologies, or ICT for short, help realize the smart power networks of the future?

This report answers this question, by presenting the key findings of the European project CRISP. It outlines the role of Internet/Web based architectures and standards, and explains the practical potential of advanced technologies such as intelligent agents and electronic markets. It discusses the results of studies on decentralized control, grid operations, and service applications in power networks that will have a high degree of distributed and sustainable energy resources. It summarizes field experiments carried out on fault diagnosis, intelligent load shedding, dependability and security, and automatic supply-demand response.

Thus, this report gives a clear picture of how the grid will evolve as a critical infrastructure in the digital age, and it clarifies the many benefits that ICT has for energy and power.

1. The Power Role of Information and Communication Technologies

Information and Communication Technologies, or ICT for short, are indispensable to manage the energy networks of the future, in which distributed energy resources play an important role. Already today, ICT offers significant capabilities for handling complex networks at affordable unit costs. We show in this report how innovation with advanced ICT will bring further benefits for sustainable development and growth of the power grid.

Several trends in ICT for power are instrumental in shaping the energy networks of the future.

Providing universal connectivity

ICT creates universal connectivity between a large variety of grid devices, both big and small power production resources, network nodes, and local loads. This provides new and better technical foundations for online distant control of highly distributed networks on an increasingly large scale. Universal connectivity is a key enabler for the proper management of any future energy network.

Managing services over Internet and Web

ICT provides new ways for real-time interaction between suppliers, distributors, and customers in the grid. This is especially due to the Internet and the Web. Timely and high-quality information on the status of the grid becomes easily accessible to all stakeholders. Internet/Web and associated Service Oriented Architectures enable new electronic services based on two-way communication between suppliers and customers. 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.

Increasing the intelligence of the grid

Advanced ICT, especially in software and information systems, effectively injects intelligence into the grid. The electricity system inherited from the 20th century has been a reliable but centrally coordinated system. With the liberalization of markets and the spreading of local, distributed and renewable energy resources, top-down hierarchical control of the grid no longer meets the modern requirements. Tomorrow’s grid needs decentralized and more intelligent ways for information, coordination, and control of the grid to serve the customer. To achieve this, ICT is a crucial ingredient.

Making the critical infrastructures of ICT and power work together

The networks for power and for ICT are both infrastructures highly critical to the functioning of today’s society. Moreover, they have become increasingly interdependent. The aim of European research is to make these two critical infrastructures work together better, as this is a key component of the future power networks. They need to become more intelligent, self-organizing, self-managing, self-learning and self-healing. This philosophy of achieving distributed intelligence in the electrical power system has been explored in the European project CRISP. You will find its key results in this report.

2. Innovating Grid Architectures

New grid architectures are required for the future Electrical Power System (EPS). They must be able to integrate distributed energy resources (DER) and renewable energy sources (RES) efficiently on a large scale. To that end, they must incorporate a high level of distribution automation, with important network operation as well as market exchange functions running in a real time mode. Actors from what are now very different worlds (power and electrical engineers, market experts, and ICT specialists) have to closely collaborate to achieve this.

If we look at the current state of the art in ICT and ask what concepts are best suited for the emerging distributed EPS, we see two basic technologies – on top of Internet/Web – that are worth to be exploited further. These are multi-agent systems (MAS) technology and electronic markets. With the liberalization of the electricity systems, the use of markets is already widespread at a national and international scale, witness day-ahead markets such as NordPool and APX. However, if combined with multi-agent technology, electronic markets can be used much more widely at a smaller scale as a foundation for various technical coordination functions in the grid or in customer services.

"Agents" are pieces of software that represent someone or something. Specifically, they may represent DER and RES installations. Agents can provide online real-time information about the status of devices, and communicate with other agents about the allocation of resources. If they are designed to negotiate about production or consumption of electricity and/or ancillary grid services, and communicate this to the controller software of the represented devices, the grid would become much more intelligent and reliable. These concepts have been explored within the CRISP project for several different applications in the power system.

Grid cells and Smart Grid Automation Devices

A proposed grid architecture that is oriented towards more flexible and distributed network operations, are "cells" of the grid that are managed by an agent, called the Smart Grid Automation Device (SGAD). Figure 1 illustrates a simple case of four grid cells that connect four remote HV/MV substations. Two agents are shown at the left and the right, together with their internal cell area. The role of the SGAD concept is to act as the ICT agent-based node that caters for all the functions a grid cell has to perform in communicating with other grid cells.

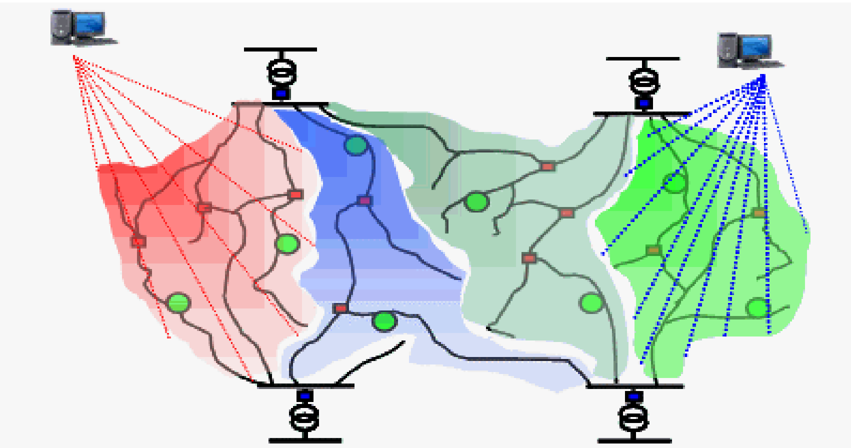

Figure 1: Grid architecture: the cell concept.

The separation into sub-networks as it follows from the cell concept extends to all functions that could be automated in real time. The local SGAD agent downloads and updates its part of electrical map of the network – say, by a specific link with a database located in a regional control room – using local communications and analysis to make local decisions, for example, on changing the configuration of the cell or on controlling loads, distributed generation or specific devices. The proposed cell concept may thus help to coordinate the different levels of ICT access inside the network, enabling a global parallelization of sophisticated and real-time network functions.

Local information by SGAD agents, for example about future power production/consumption expectations, is sent upward to the higher levels of the grid. There, this information is progressively aggregated and processed, whereby the global balance is checked and the main decisions are taken. If, as a result, the declared power reserve is able to act on this aggregated information in real time, the stability and the robustness of the total EPS network would be strongly reinforced by the DER contribution. Combining many grid cells with their associated SGAD agents leads to a grid architecture for a Large-Scale Virtual Power Plant (LSVPP, see Figure 2).

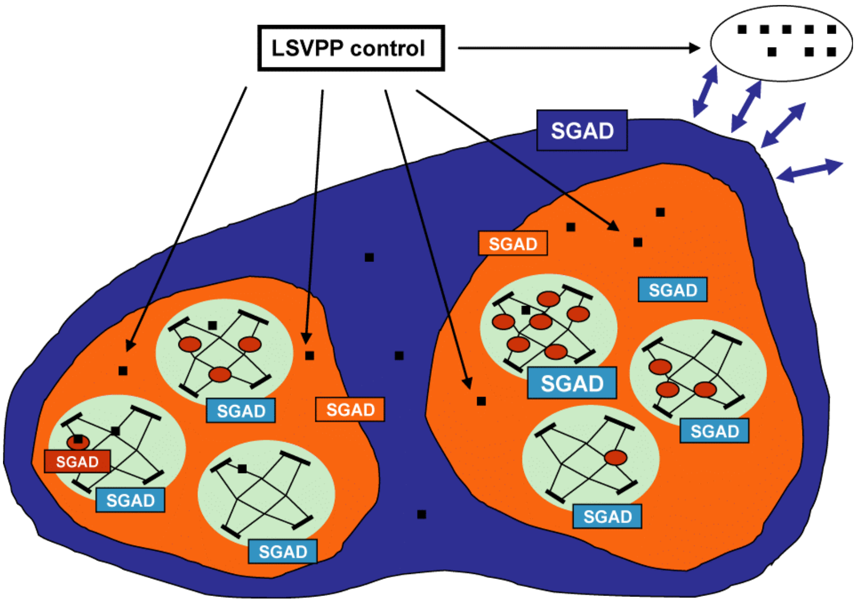

Figure 2: Agent-based Smart Grid Automation Devices within a Large-Scale Virtual Power Plant.

Agent-based fault handling

Fault detection and reconfiguration is one of the operations that can be automated along these lines 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.

The network for the fault experiments (see Figure 3) was built using standard computers and Ethernet links, a simple TCP-based communication protocol, dedicated traffic shapers, and the Arene real-time network simulator. This creates a dynamic environment in which one can easily test the behaviour of several different system configurations. The use of a simple and standard communication protocol allows one to determine a 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.

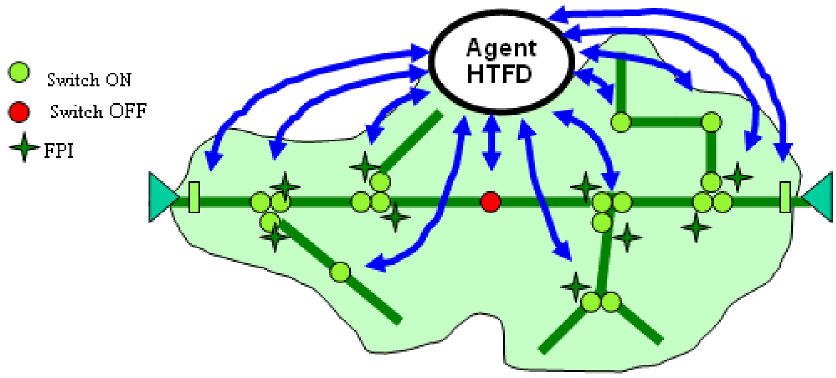

Figure 3: Layout of a grid cell, with the communicating SGAD agents managing the EPS services and their link to the HTFD fault diagnosis tool.

Tests of fault detection, localization, isolation and reconfiguration

Extensive tests have been carried out on EPS fault detection, localization, isolation, and reconfiguration, in Grenoble, France, and for the ICT performance part in Ronneby, Sweden. Our proposed solution has been investigated for existing distribution networks as well as for future scenarios with a massive insertion of distributed energy resources.

Figure 4 shows an experimental study result. The experiment scenario contains the following steps:

1. Fault Passage Indicator (FPI) activated; the fault protection system sends information to the HTFD tool.
2. Evaluation of this information and associated computation by the HTFD tool.
3. The HTFD tool locates the faulty section and proposes a solution to clear the fault.
4. The HTFD tool is informed that the fault is still present at the second re-closing sequence, and the decision is taken to try to isolate the faulty section.
5. The circuit-breaker is open, and the switch operation for isolation and reconfiguration is launched.
6. The normal situation is validated, and a reset of the system is performed to be prepared for a next fault occurrence.

The re-closing sequences are achieved by the protection system to avoid nuisance tripping: this technique, widely used by Distribution System Operators (DSO), enables to quickly clear more than 90% of the occurring faults inside MV networks. The HTFD tool is informed of the state of the circuit-breakers and of the fault current magnitude by the digital protection relay.

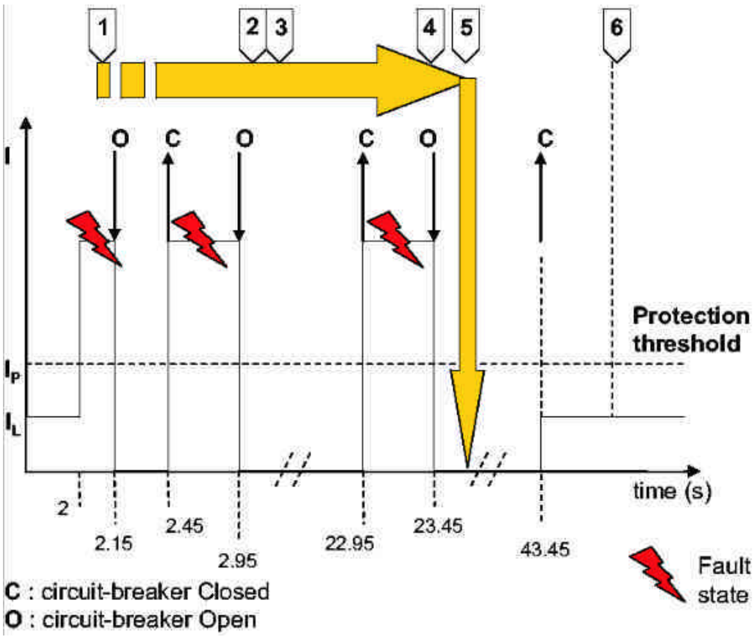

Figure 4: HTFD fault diagnosis tool used in parallel with an automatic re-closing system.

Modular communication and function boxes for EPS applications

In the experiments, messages are exchanged between the devices and the SGAD in a few tens of milliseconds for data communication speeds above 100 kbit/s. The tool launches a location evaluation 1 second after the arrival of the first data indicating the fault occurrence. In situations with lower data communication speeds, if the information received at 1 second after the first message is not sufficient to indicate a single location in the network, another evaluation is launched after 2 seconds, and so on. The fault detection application is not too much constrained by the automatic re-closing system because it entails a fixed interruption duration varying between 15 and 30 seconds.

The measured communication streams indicate the importance of the data flow rate for the message transmission. Our HTFD application shows that the fault may be isolated correctly in less than one minute, even if the communication speed is very low (10 kbit/s). Without the automatic re-closing system a possible isolation of the elementary faulty section may be achieved in less than 10 seconds. These results open up the opportunity to drastically reduce the time of interruptions observed today on the distribution EPS.

Our 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. Intelligent Supply-Demand Matching

Electricity distribution infrastructures are currently based on a hierarchical, top-down flow and distribution of power. Liberalization has led to reduced investment horizons and to unbundling of utility activities. Power networks show a decreasing reserve capacity and increasing load factors. Integrating an increasing proportion of renewable energy sources with intermittent and partly unpredictable generation necessitates more flexibility of the power grid concerning demand and supply. Recent, high-impact, cascading power outages in highly connected HV transmission networks add to the need for more distributed generation in the power grids to spread the risks.

Increasing constraints on the operation of power networks during the last decade are reflected in strongly varying day-ahead market prices. Figure 5 shows a three-dimensional plot of the prices for a complete year, and illustrates this very clearly for different parts of Europe.

Bottom-up features of an intelligent grid

Renewable energy systems currently have a limited role in the total power infrastructure for maintaining uninterrupted operation and power quality. They are tolerated rather than that they actively contribute to total grid stability. This also holds for the power pricing and market aspects. Introducing a substantial amount of RES in a distributed setting requires such systems to be connected in an intelligent and more dynamic way than today.

Optimizing the operation of a mixed power infrastructure, for instance in a commercial or residential area, requires access to operational context information from higher numbers of power network nodes from both the supply and demand side. The way to satisfy such needs is to have a bottom-up rather than top-down architecture of the physical power distribution grid and its accompanying ICT infrastructure. An online dynamic balancing model, then, is required in which one of the main issues will be what the real-time expected demand is, and what load is to be inserted in the network as a result.

Along these lines, in the EPRI Electricity Technology Roadmap and the IntelliGrid architecture, a new mega-infrastructure is envisioned that contains a combination of – partly customer-managed – energy/information networks to meet these challenges. Furthermore, information models are defined as a framework to set new standards to the industry. Two major developments in distributed intelligence are of paramount importance in this respect:

(i) The next, intelligent WWW generation known as the Semantic Web, and the deployment of (Web) Service Oriented Architectures (SOA); and

(ii) Intelligent agent and multi-agent systems as a distributed software architecture particularly suited to applications in a networked and decentralized environment.

These ICT developments will strategically impact the energy industry sector by enabling new types of electronic energy services.

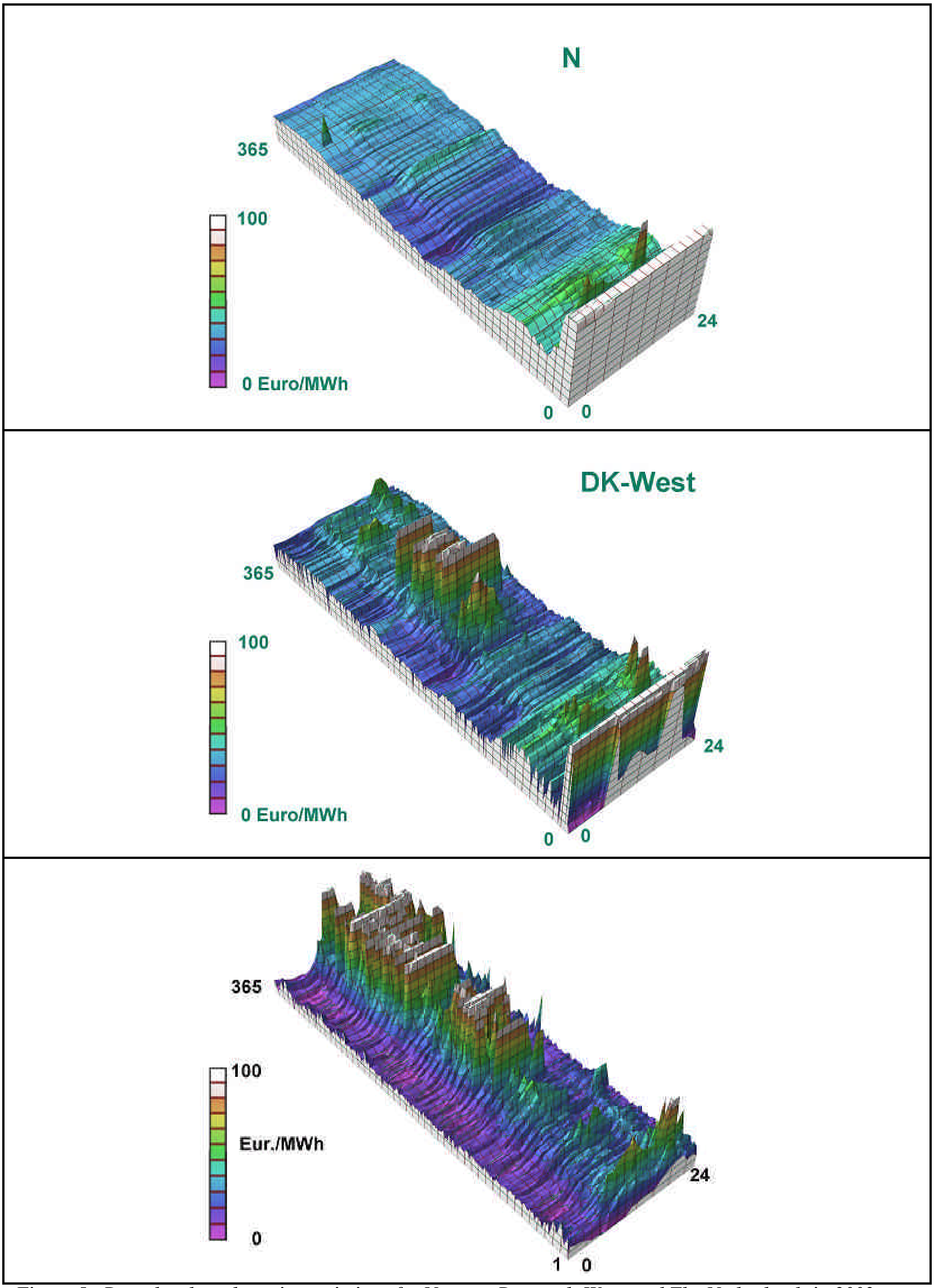

Figure 5: Day-ahead market price variations for Norway, Denmark-West, and The Netherlands in 2003.

Electronic power markets for massive distributed coordination

An intelligent grid infrastructure poses challenges to power network design but also provides new instruments for optimal and cost-effective operation of the grid. One is the use of electronic power markets as a technical coordination mechanism within cells of the grid. Here, agents represent individual DER devices, communicate with each other within a grid cell, and negotiate online in an auction-like fashion about their willingness to produce or consume power.

One application of such agent-based electronic markets is to combine different DER and RES into a commercial cluster. In most liberalized countries electricity producers and traders forecast their production/consumption on a daily basis, and communicate this to the transmission system operator (TSO). At all times, total demand and supply must be in balance. Deviations that occur real-time are compensated by the TSO through contracting “regulating power”. The costs of this real-time balancing process are put on those parties in the market with a deviation from their forecast.

By combining several energy resources into a commercial cluster, and by readjusting their combined output – through agent-based electronic markets – in such a way that deviations from the forecast are minimized, both the costs for the commercial cluster and the need for regulating power are reduced. Massive implementation of this concept would make grids and electricity markets more stable.

Field tests of a real-time power imbalance reduction system

The CRISP project has fully developed the new ICT methods needed for this concept of power balancing through electronic market methods in an intelligent grid. The real-time imbalance system was designed and implemented as one of the CRISP field experiments. The field test is carried out with communicating DER devices located in different parts of The Netherlands. It aims at automatically reducing the imbalance in a real-world portfolio of a commercial trader. The intermittent character of sources such as wind farms is an important cause of the portfolio imbalance. The imbalance price development in The Netherlands is shown in Figure 6.

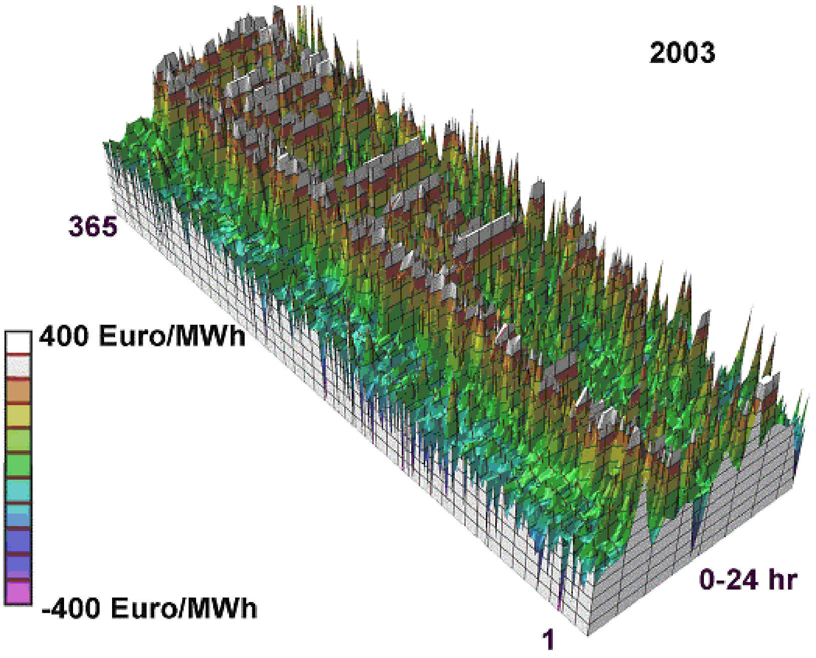

Figure 6: Imbalance price in The Netherlands in 2003.

Figure 7 shows the actual field-test configuration. At the supply side, the experiment includes two wind turbine parks, an emergency generator, and CHP installations connected to a heat distribution network in a residential and a small local industrial area. The demand side in the portfolio consists of controllable cooling loads in a meat-processing factory and a cluster of houses utilizing electric heat pumps. A day-ahead profile of the portfolio is constructed using installation models of the nodes in the field test and forecasts from wind prediction models.

This profile is then compensated in real time for over/under-realization: the control strategy is adapted based on the outcomes of the electronic market, using agent algorithms operating over an ICT network. In the field test, the agent-mediated control resulting from the electronic power market is compared with simulated control, derived from models of the individual installation's processes. As electricity consumption and production profiles depend on the time of year, the field test covers all four seasons over 2005-2006.

Figure 7: Field test configuration of the supply-demand power matcher.

Some lessons learned

The concept of power balancing via agent-based electronic markets turns out to work successfully. Experimental results indicate that over- and underproduction of the wind parks induce price changes on the local cluster "market", as can be seen in figure 8. The price formation process based on the electronic market then triggers the expected control change steps, which in turn indeed leads to a decrease in the total power imbalance. As an illustration, a delayed filling of the boilers in the residential homes automatically compensate for under-realization by the wind parks. In the field experiment the imbalance reduction is significant: about 40%, mainly by compensating for over-production, as can be seen in figure 8 where the blue line coincides with the x-axis. Underproduction could not be compensated easily during the period in the figure 8, since the CHPs were already planned in full operation, and the emergency generator lacks capacity. An improved cluster configuration, that differs over the seasons, may even lead to much higher imbalance reduction. The electronic market system has been baptized "PowerMatcher" (see also http://www.powermatcher.net), and is in fact now rolled out in new applications.

An important general conclusion is that *current mainstream ICT* is able to satisfy the requirements for such advanced distributed energy service applications that connect to the process control systems of customers. Agent technology, using algorithms from micro-economic market theory for massive coordination, offers a scaleable 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.

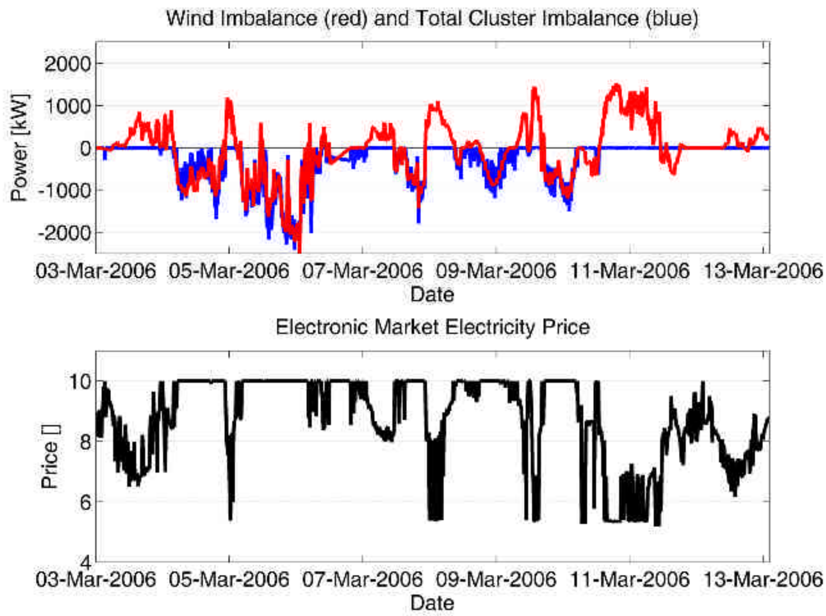

Figure 8: Price development versus wind imbalance (red) and cluster imbalance (blue)

The PowerMatcher

The field test demonstrates that the PowerMatcher principle works in practice and can help to reduce substantially the imbalance of portfolios with substantial amounts of variable generation. Main issues to prepare for a massive roll out are increasing the flexibility of the installations in the portfolio and of the effects that will occur in practice, such as starting-up and switching-off delays. Another aspect is the robustness of the hardware and software involved.

The PowerMatcher can be used for other barriers to Wind and Solar as well. In fact the flexibility of the PowerMatcher enables applications in a number of areas in which energy balancing can be profitable, from controlling of virtual power plants to energy management in local networks with a large share of local generation.

In a number of spin-off projects the PowerMatcher is and will developed further for these different purposes. At the same time a commercialisation process is being considered.

4. Distributed Voltage Management

Since the beginning of the electrification era, load shedding has been a last resort to save an electric power system from instability. For much of the 20th century only frequency controlled load shedding was applied. By the end of the last century also voltage controlled load shedding was emerging. However, the concept of load shedding to save the power system integrity is not very well developed. Even today, basically all load shedding schemes shed load by the trip of a medium voltage circuit breaker, letting a whole village or a major part of a town without electricity. The large disturbances in power systems around the world in recent years clearly show the need for better tools to mitigate widespread disturbances approaching a system breakdown.

Intelligent load shedding

The concept of "intelligent load shedding" can be divided into different areas, answering the classical questions *where*, *when* and *how much* to shed. One side of the concept is to apply intelligent methods to identify the power system conditions under which load shedding should be applied (basically referring to *when*). The other side of the concept is to perform the load shedding itself in an intelligent way (basically referring to *where* and *how much*). The work on intelligent load shedding in the CRISP project has resulted in various new technical principles and dedicated algorithms. These algorithms are a powerful support tool for the system operator during critical situations.

Making load shedding more intelligent is not really difficult. It ranges from very straightforward methods – that can be implemented by any utility or system operator with today's technology and products, even without sophisticated communication schemes – to schemes including the most modern ICT, based on agents and bilateral online negotiations. Many of the concepts are based on well-proven technology and suitable products are available.

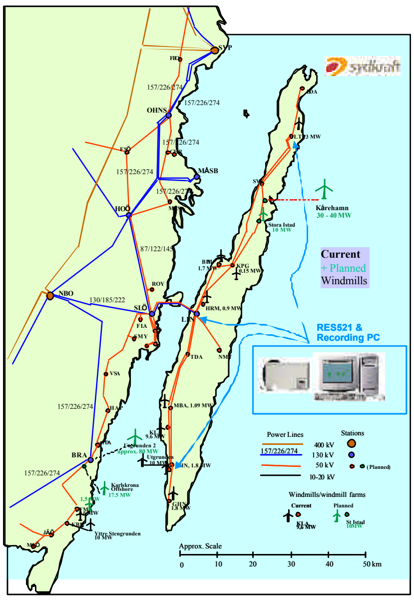

Figure 9: Power grid on the Swedish island of Öland.

Experimental studies of intelligent load shedding within the CRISP project have focused on the interaction between load and supply in power systems. During the summer of 2003 three phasor measurement devices have collected data from faults and disturbances in the radially fed power grid on the Swedish island of Öland (Figure 9), where a considerable amount of wind power generation is present and planned.

Under-voltage as a good instability indicator

Recordings from the Swedish blackout in September 2003 provide highly valuable information on load response to a disturbance comprising the combined effect of loss of generation and loss of transmission capacity. These data also clearly illustrate the power system requirements for a smooth restoration process.

The simplest way to detect a near voltage instability is by under-voltage relays. The voltage level is a good criterion, but the settings of the protection scheme have to be adjusted to each individual system. Since all power systems are exposed to “normal faults” – without being in a “close-to-voltage-collapse-situation” – the time delay for the under-voltage protection relays has to be longer than the time delay for the backup clearance of shunt faults. The transmission system voltage some 100 km north of the affected area during the Swedish blackout in 2003 is shown in Figure 10.

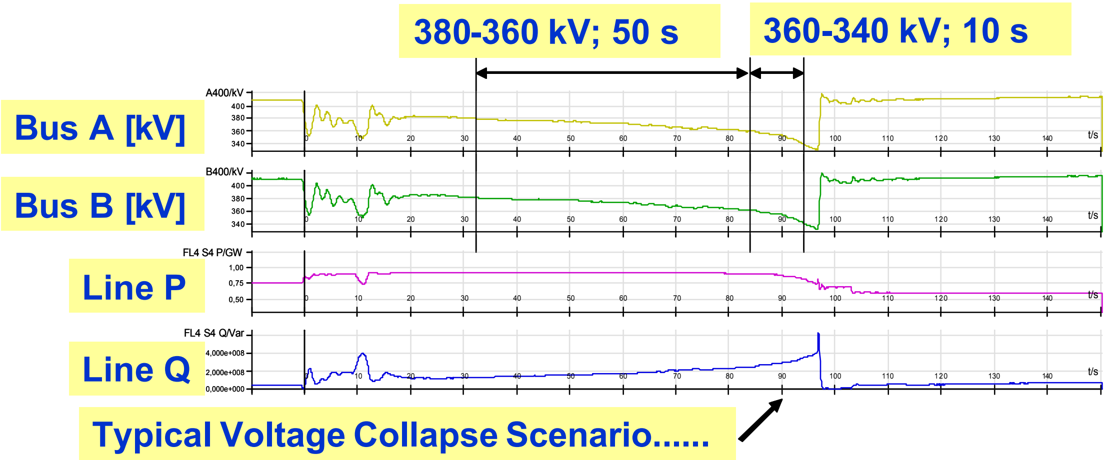

Figure 10: Recordings from mid Sweden during the blackout on 23 September 2003.

We see that the transmission system voltage is slowly decaying after the initial disturbance, and for about 50 seconds it is in the interval 380-360 kV, and for 10 seconds it is in the interval of 360-340 kV. The voltage levels in the affected area were even lower. These curves clearly indicate that there is plenty of time for an under-voltage based scheme to take actions. We also see that the active power flow to the affected area is decreasing, while the reactive power flow is increasing. This is typical for a voltage instability scenario. It is important to measure the voltage on the transmission system level, since transformer tap changers will keep up the voltage on lower levels during the voltage collapse event prolongation.

On-load tap-changer control

The major disturbances throughout the world clearly illustrate the need for different modes of voltage control, since the requirements in abnormal conditions, sliding towards instability, are very different from normal operation conditions. The CRISP results show that there is a great potential to improve tap-changer control in order to perform properly also under disturbed conditions. Figure 11 shows the tap-changer position for a power transformer, from the transmission level to the sub-transmission level in the affected area, at the end of the Swedish blackout in 2003. The tap changer is designed only to keep the voltage at the low voltage side within certain limits around the set point. When the transmission side voltage decreases, the tap changer operates to fulfil its task. As a consequence, the tap position increases nine steps within 80 seconds, keeping up the downstream voltage – and thereby the load – drawing more reactive power from the already weakened transmission system.

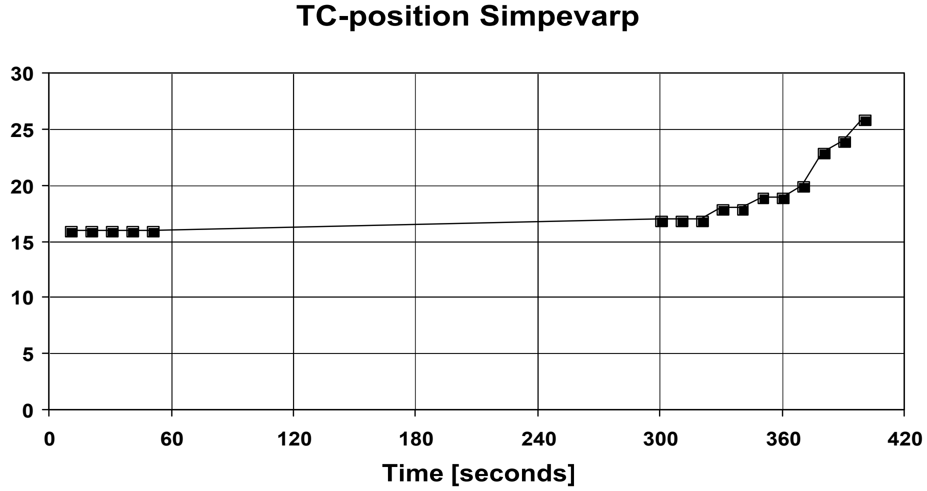

Figure 11: Transformer tap-changer position by the end of the Swedish blackout.

We believe that this tap changer could have been more “intelligent”. The main purpose of the on-load tap changer (OLTC) is to keep the low voltage (LV) side busbar voltage within a preset dead band. Thus, it compensates for the voltage drop across the power transformer impedance caused by the load current. Therefore an OLTC shall react and change position in accordance with the LV side load variations. However, the OLTC will also react to abnormal voltage variations on the high voltage (HV, in distribution systems the supply) side of the power transformer. Often such a reaction is not desirable because it just further increases the total load on the HV system (i.e., the transmission system). In particular, such behaviour shall be prevented during critical operation states of the transmission system, such as a slow power system voltage decrease.

Great potential for improvement

All currently commercially available automatic voltage regulators (AVRs) just measure the LV side voltage of the power transformer in order to make decisions about the OLTC position. Such a principle has as a major drawback that it typically speeds up a power system voltage collapse. However, some modern intelligent electronic devices (IEDs) used for such automatic control do have the capability to measure the power system voltage on both sides of the power transformer, as shown in Figure 12.

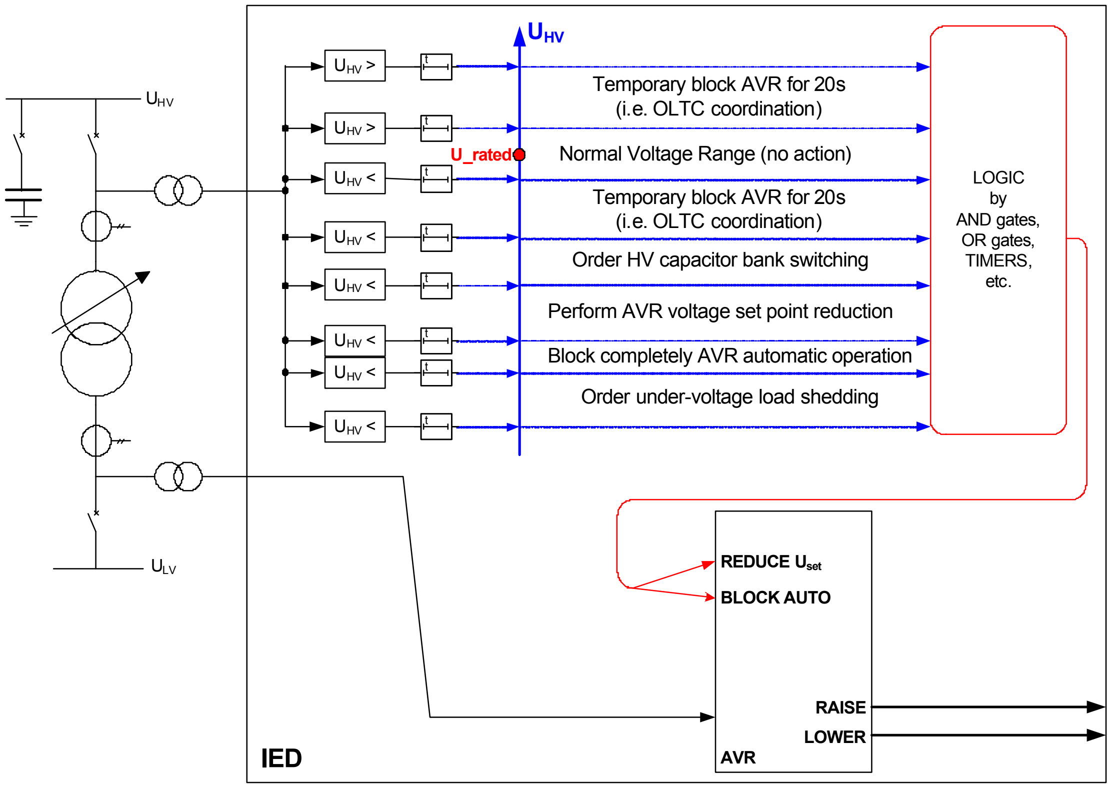

Figure 12: Improved automatic on-load tap-changer control scheme.

Voltage transformers are typically available on the HV side of the power transformer due to other reasons. By using a number of over- and under-voltage triggers, it is then possible to monitor the HV side voltage magnitude and consequently influence the operation of the AVR or other equipment in the substation. For the best scheme security it is desirable to measure all three phase-to-earth voltages from the HV side, in order to take necessary actions only when all three voltages are above or below the pre-set level. Therefore, operation of the AVR will be influenced by the measured voltage level on the HV side of the power transformer.

The following typical actions can then be taken:

- Temporary AVR block (say, for 20 seconds).
- Temporary AVR voltage set point change (typically reduction).
- Complete AVR block until manually released by the system operator.
- HV shunt capacitor (reactor) switching.
- Under-voltage load shedding.

Such a scheme can be tailored to strict requirements of every power system operator and to characteristics of the individual power system. In addition to excellent performance for HV side voltage variations it can also be used to improve time coordination of the OLTCs connected in series as well as to minimize the number of necessary tap-changer operations.

Conclusions for immediate implementation

From the CRISP experiments on intelligent load shedding we extract the following conclusions and guidelines that can be immediately implemented in any power system:

1. *Load shedding can be much improved.* The consequences of large power system disturbances can be significantly reduced by the use of intelligent load shedding. The power system integrity can be saved in a critical situation by: smooth load relief achieved by cell-structured intelligent communication and control systems, keeping track of load objects suitable to shed, and agent-based methods to identify the power system conditions in order to decide where, when and how much load to shed.
2. *Voltage levels are good candidates to identify voltage instability problems and can be used to initiate load shedding.* From the analysis of the Swedish blackout in September 2003, we learned that the voltage levels in the transmission system are good indicators to identify transmission capacity problems. Enough time is available to take counter actions, such as load shedding.
3. *Use the more intelligent tap-changer controller.* Tap changers may be the component that finally pushes the power system over the edge to a blackout. However, tap-changer controllers that also include the upstream voltage in the algorithm are available, and provide a superior solution to this problem.

5. Dependability and Security of Critical Infrastructures

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.

From SCADA to Service Oriented Architecture

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.

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.

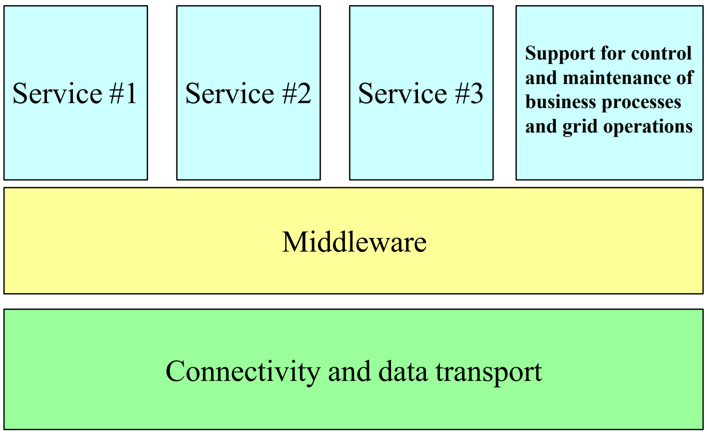

Figure 13: Service Oriented Architecture.

To achieve such goals, new information systems architectures have recently emerged in ICT that are known as Service Oriented Architecture (SOA, Figure 13). 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 (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.

Performance of ICT networks and protection of the grid

A Service Oriented Architecture has been successfully used to support the various CRISP applications and tests. 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 experiments on fault handling as discussed in Chapter 2. This is illustrated in Figure 14, displaying toolbox screenshots of two different phases of the service chain: fault detection – fault localization – fault isolation – EPS restoration, corresponding to a grid cell layout as depicted in Figures 3 and 4.

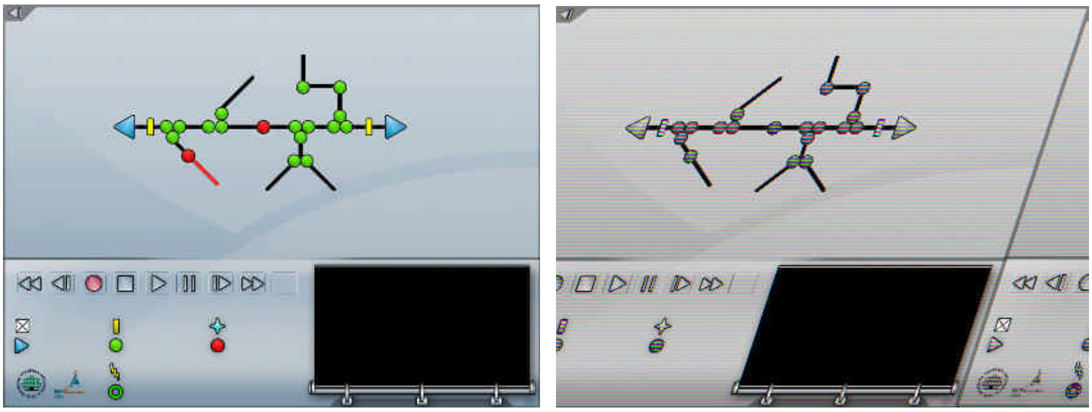

Figure 14: Two phases in a fault diagnosis experiment visualized by the CRISP support toolbox.

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. Generally, it turns out to be possible to customize real-time efficient ICT communication in EPS based on the IP network protocol.

Secure software execution

Most contemporary models aiming at trustworthy and dependable software focus on assessing and testing the code itself (black and white box testing, etc.). A special feature of the CRISP approach is that it has been oriented towards assuring correct *execution*. We have to that end identified and successfully tested different mechanisms supporting assessment and protection of the *run state* of execution of services in a Service Oriented Architecture.

The toolbox and test-bed displayed in Figure 14 have also been used to validate our 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.

This work yields several types of protection mechanisms for secure software execution (self-healing models):

- *Immunization*: a method that affects an execution environment in such a way that a program that normally (without protection) would be exploited is secured so as to continue normal operations. An immunization method may perform operations other than just immunizing the environment, for example, by writing a diagnosis message to a log file. In fact, this is an example of feedback from a failure model to improve system dependability as well as support for traceability and forensics.
- *Detection*: a detection method detects an exploit *before* the system has a chance of becoming exploited. Typically, but not necessarily, detection methods take some action to *prevent* the system from being exploited, most often by killing the processes associated with the execution environment.
- *Reducing system consequences*: a method reduces system consequences if it modifies an execution environment so that, if exploited, the consequences for the system are less severe than without this protection.

The experimentally verified overhead for these self-healing mechanisms is low, in the order of micro- or milliseconds.

Challenges ahead

As we have seen in Chapters 2-4, 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.

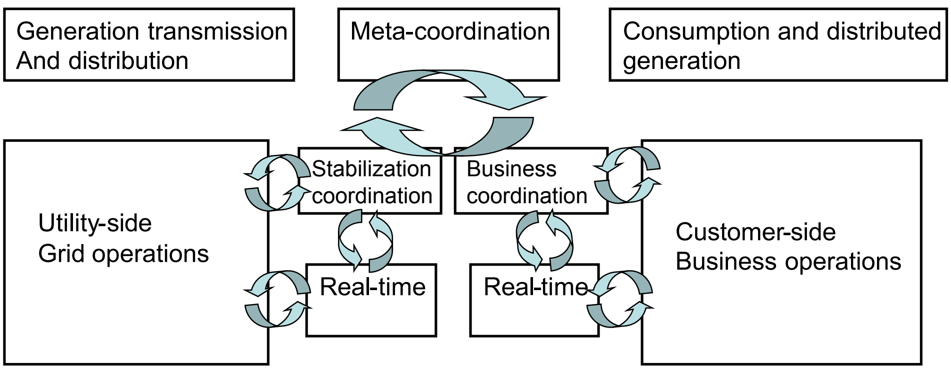

Figure 15: Coordination patterns in future virtual power plants.

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 14, 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 15).

Information protection

Information protection in such a setting can be based on the same principles as outlined earlier for secure software, namely, by focusing on secure execution. As a starting point, one may say that *“information = representation + interpretation”*. Classical information protection (Confidentiality, Integrity, Availability; also known as the CIA model) mainly protects the representation by means of cryptography, PKI, and access control such as passwords. These methods have many known weaknesses and limitations, among them scalability and maintenance issues.

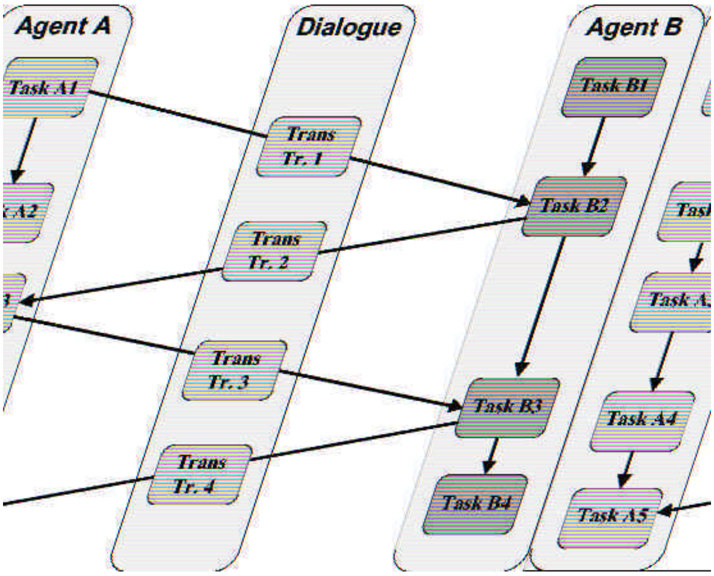

Figure 16: Dialogue models provide ways to analyse system coordination patterns.

A useful alternative approach is not to focus on the (static) representation side of information but on its (dynamic) interpretation, that is, on its computer *processing*. The backbone of such an approach is to analyse the overall coordination patterns, and then introduce constraints that disable system behaviours unwanted from the protection point of view. This can be modelled with the help of dialogue models familiar from agent communication and knowledge engineering (Figure 16).

Such models take task structures and associated agent transactions as their focal point. From there, one can define information protection mechanisms for the various components, including individual tasks, workflows, transactions, information items, and supporting agent capabilities and access rights. For example, in market-based supply-demand matching (Chapter 3), DER device agents carry out tasks such as bidding. Their dialogue is a transaction process, in which their bids contain private information items about their predicted need for power and the prices they are willing to pay – all information that must be protected. Although there is still quite some way to go here, the CRISP project has identified and partly validated mechanisms for dependable and secure business services that will be important in future cell-based grid architectures and virtual power plants.

6. Intelligent Agents and Electronic Markets

In previous chapters we have sketched how established ICT technologies and Internet/Web standards, and associated Service Oriented Architectures, are capable (already today) to cater for many of the functionalities of distributed energy networks. We have also indicated how advanced ICT technologies such as software agents and electronic markets are promising for decentralized control of energy network functions and services. These innovative technologies are the ones that make the grid more intelligent and self-organizing, and therefore deserve a further explanation.

Agents

Software agents represent a new type of Information Systems (IS) architecture particularly suited to distributed applications in networked environments such as Intranets, Internet/Web, or the electricity grid. Agents offer ways to embed intelligent system techniques in large distributed IS. Figure 17 offers a definition and overview of the characteristics of intelligent agents.

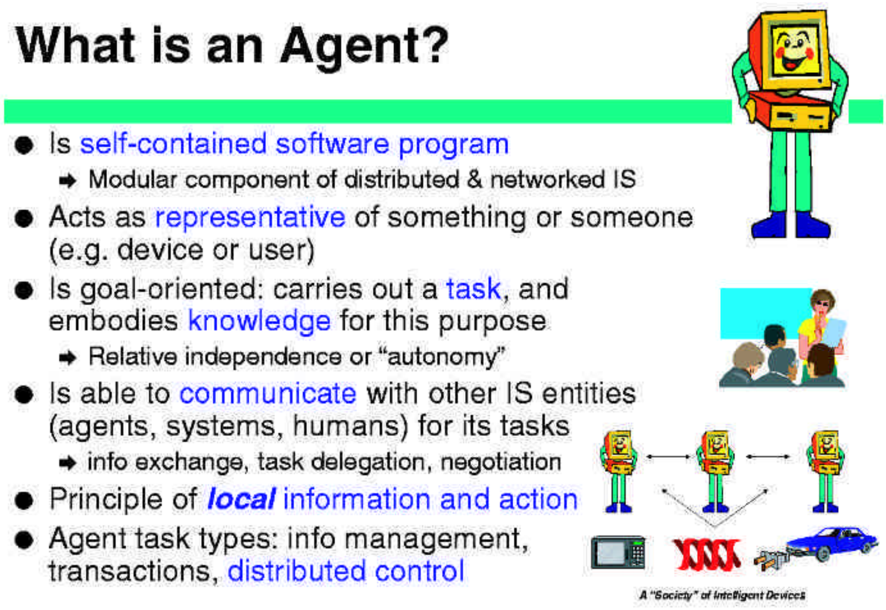

Figure 17: Definition and characteristics of intelligent agents.

Agents are well known from Web Services. They are also essential to the various applications discussed in Chapters 2-5. On their own, they provide a form of local intelligence, as they can locally reason about available information and act upon that. The real strength of agents, however, appears when we combine many of them into a multi-agent system (MAS). Then, if they communicate and share relevant information, one can build forms of *networked or global intelligence* – that is, information system versions of the well-known maxim that "many know more than one".

e-Markets

A specific example of a multi-agent system is an electronic market. Suppose you are an agent representing a DER device, such as a Combined Heat and Power (CHP) installation producing electricity while heating a large office, or a cooling installation consuming electricity to control the temperature in a cold store. Today, the overproduction of electricity of the CHP is normally sold at low prices to an external party, your utility company. In contrast, the cold store will probably purchase its electricity at high prices from its utility. This discrepancy between the low retribution prices and the high delivery prices, however, opens up the opportunity for mutually beneficial *local electricity trading* between the CHP and the cold store, especially if the CHP is able to deliver its electricity when the cold store actually needs it. The possibility of direct local trading would save money for each DER device. If not just two but a large number of DER participants take part in the trade, a *market* emerges. By means of ICT the trade between the DER parties can in fact be fully automated as a local *electronic power market*, where prices are established according to the supply and demand of power in the local cluster or cell.

Conceptually, intelligent agents act on electronic markets in very much the same way humans do on auctions: they assess their goals and available information; on this basis they construct and submit bids (see Figure 18), react to the going market prices, and try and optimize their situation.

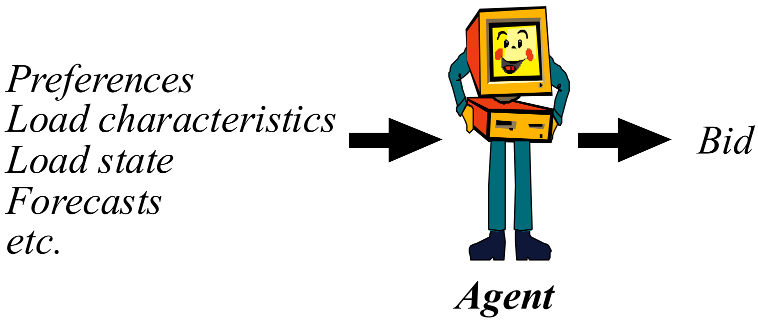

Figure 18: A software agent establishes its preferences, collects relevant information, and on this basis constructs bids on an electronic power market.

Formally, following the mathematical theory of micro-economics, markets are mechanisms that optimize the allocation of resources (such as power and money) over a large number of actors in a decentralized way. When to produce or consume energy can be viewed as an optimization process: a heating or cooling system in a building optimizes its behaviour with respect to the objective to stay close to a predefined temperature. However, markets add a dimension to this: dynamic price information. So, the optimization is not only about getting optimal functionality, but dynamically doing so at minimum cost or maximum profit.

Novel demand response and supply-demand matching schemes as discussed in Chapter 3 are based on this principle. Also, an electronic market power game called ELEKTRA has been developed within CRISP, to let people experience how these concepts work in an entertaining and educational way.

Decentralized control

A core issue in resource allocation through markets is how to express the agent's goals in terms of preferences (cf. Figure 18). In microeconomic market theory this is traditionally done by *utility functions* or *demand functions*. These are two complementary ways to express preferences, the former having the resource as the independent variable, and the latter the price, as depicted in Figure 19. Supply is equivalent to negative demand, and hence both are formally expressed by the same kind of functions.

The local electronic markets as developed in CRISP serve a rather special purpose. Usually, trading via electronic markets aims to achieve a proper resource allocation (take eBay as an example). In contrast, the CRISP electronic markets go a step further: their outcomes are not just optimal resource allocations, but they also provide the set points for decentralized control of large-scale systems of heterogeneous DER devices. To this end, agent utility or demand functions are converted to what control theory calls performance indices. In the CRISP approach, these control performance indices include dynamic price information.

Thus, electronic markets provide a principled foundation for model-based predictive and optimal control of large-scale systems in a fully decentralized way.

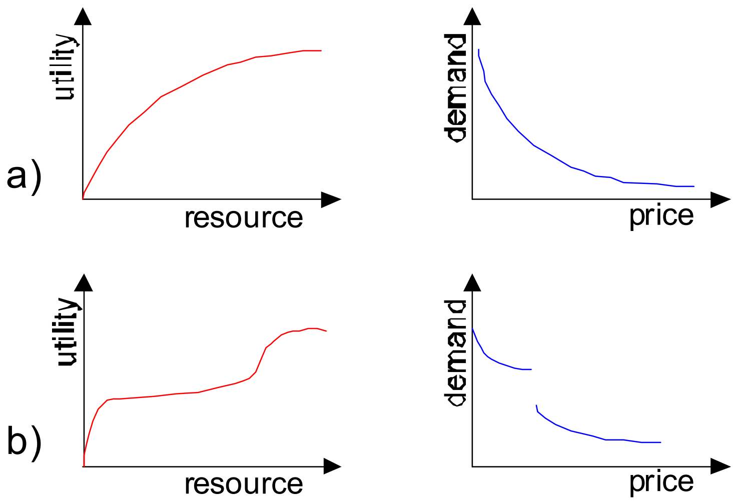

Figure 19: (a) Classical utility and demand function, and (b) non-classical utility function and corresponding (non-continuous) demand. The latter also occur in power e-markets.

Algorithms

To carry out electronic markets for decentralized control automatically, one needs special computer algorithms. Although markets are considered to solve optimization problems with many actors, most well-known numerical optimization or operations research techniques are not really suitable, because they typically work on the basis of centralized, closed-system and offline settings. This is not going to work in the open, online, and Internet-based environments of today.

Therefore, CRISP has also developed and tested new agent-based e-market protocols and algorithms that handle fully distributed and online situations with dynamic prices. Generally, suitable market algorithms for control of distributed EPS are non-trivial: they involve a multi-dimensional optimization that displays multi-commodity dependencies in the agent preferences.

We have successfully developed and tested various market algorithms, including distributed Newton-Raphson styled continuous optimization, integer programming based techniques, and tailored mechanisms utilizing specific combinatorial properties of power markets. Tree-structured market mechanisms are an example of the latter: they give bidders the possibility to state dependencies one cannot express on a traditional day-ahead electricity market, whereas information communication as well as market computations stay manageable.

The actual choice of a market algorithm depends on the specifics of the application. As general criteria we have scalability, robustness, efficiency, the convergence speed of iterative algorithms, and the costs of the communications between agents. Some of these criteria may be in conflict and, generally, there are tradeoffs that must be considered in the light of the specific application. On the other hand, there is now an extended library of market algorithms to choose from. The many CRISP simulation studies and field experiments have shown that it provides good working solutions for a wide range of distributed power applications.

Scenario simulation studies and results

With these methods, we have performed a significant number of scenario simulation studies to prepare, support, and generalize the CRISP field experiments discussed in previous Chapters. Several different scenarios and grid structures have been investigated.

Our e-market simulations have demonstrated for the Öland island case (Chapter 4) how peak power production with large wind energy parks may be accommodated in the grid with less transmission capacity using local demand response.

E-market simulations also have prepared the ground for the field test in The Netherlands (Chapter 3) to balance realized and predicted power within a DER device cluster in a commercial portfolio active on the day-ahead market. They show how the use of electronic markets as supply-demand power matchers is able to reduce the need for regulating power.

Finally, Figure 20 shows how the power flow from higher voltage grid levels through the transformer can also be reduced. The simulated LV-cell scenario comprises a residential area grid with a number of micro-CHP devices and heat pumps. The SDM electronic market yields a peak reduction of the power feed-in from the MV net by 30%. Moreover, supply-demand matching results in smaller fluctuations in local production and consumption, and a smoother profile of the external power import. In Figure 20, SDM market-based control lowers the overall standard deviation of the feed-in by 58%. All this provides evidence that supply-demand response strategies via local electronic power markets are a promising mechanism for future ICT-supported power grids.

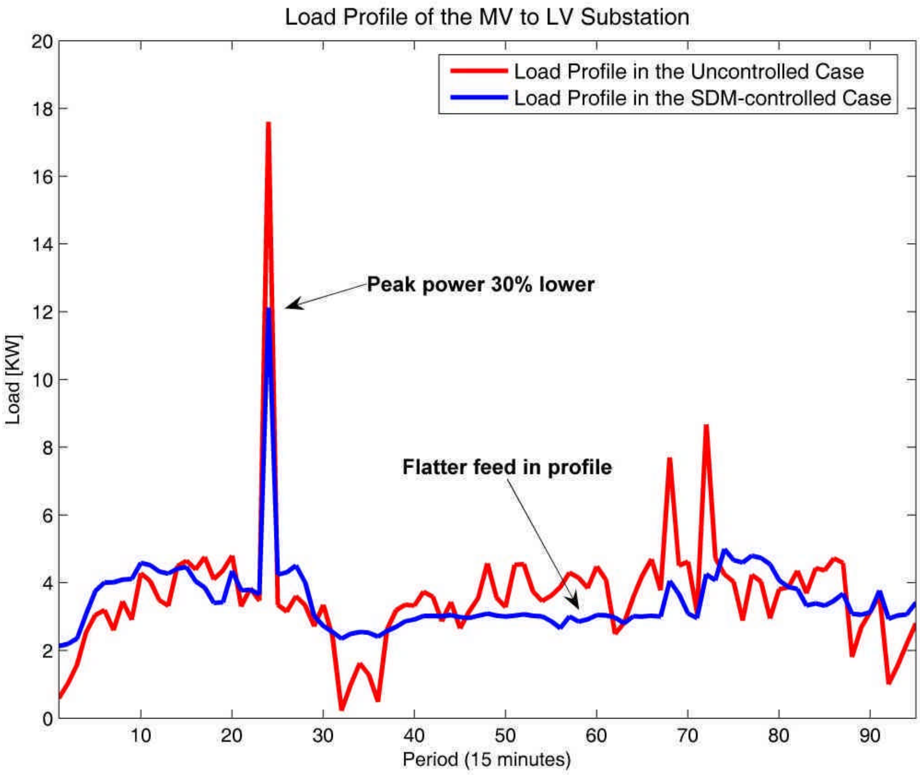

Figure 20: Electronic market simulation of the amount of power imported by a residential LV cluster from the MV grid during a day, demonstrating decreased fluctuations and power import reduction.

7. ICT to Build the Smart Power Networks of the Future

The European project CRISP has produced a range of useful insights, innovative methods, and pioneering applications concerning how ICT can help realize the smart power networks of the future. Here are some of the key findings:

- Established ICT technologies including Internet and Web standards are capable already today to cater for many of the functionalities of future energy networks. The European power sector has however not yet reaped all benefits from currently available ICT opportunities.
- Software agents and electronic markets are advanced ICT technologies that enable decentralized control of power networks, and make the grid intelligent and self-organizing.
- Agents in cell-based grid architectures are able to carry out advanced fault detection and handling functions.
- Automatic supply-demand matching by local electronic power markets in commercial DER clusters lowers power import from other parts of the grid, decreases fluctuations in production and consumption, and reduces regulating power needs.
- Under-voltage is a good grid stability indicator that can be used in critical situations as a starting point for intelligent load shedding. Great improvements may be achieved here with relatively simple means, among them more intelligent on-load tap changer control.
- Real-time performance requirements of ICT network systems can be met by properly configuring the embedded ICT in a Service Oriented Architecture. Efficient ICT communication in EPS is possible with the IP network protocol. Adequate protection can be based on special mechanisms for secure execution.
- Further research and technology development is needed on issues of interfacing, integrating and protecting power systems interlinked with ICT information systems in a robust and standardized way. This is to be done for example in the context of integrating new concepts such as the large-scale virtual power plant.
- Attention must be paid to how to align the new ICT technologies, Internet/Web standards, and grid architectures, with emerging new business and service models in the European market environment.
- Without a doubt, advanced Information and Communication Technologies are key to designing and managing future smart power networks with a significant amount of distributed and sustainable energy resources.

Information Sources and Further Reading

The methods, experiments, and results summarized in this report are based on extensive studies by the EU project CRISP. The reader may find more in-depth information on the CRISP website at http://www.ecn.nl/crisp.

Specifically, the summarized results of this report are especially based on CRISP project deliverables, as follows:

– Support observations and maintenance of the integrated ICT-power systems.
– Chapter 1: D1.1, D1.2, D1.3
– Chapter 2: D1.4, D1.7, D3.2B
– Chapter 3: D1.2, D1.8, D3.2A
– Chapter 4: D1.5, D3.2C
– Chapter 5: D1.6, D2.4
– Chapter 6: D1.2, D1.8
– Chapter 7: D3.3, D4.3

A large number of journal and conference publications regarding all aspects of the CRISP work have been collected in the CRISP deliverable D4.3 (CRISP Dissemination Compilation Report), available for download from the CRISP website.

List of abbreviations

APX	Amsterdam Power Exchange
AVR	Automatic Voltage Regulator
CHP	Combined Heat and Power
DER	Distributed Energy Resources
DG	Distributed Generation
DSO	Distribution System Operator
EPS	Electrical Power System
FPI	Fault Passage Indicator
HTFD	Help Tool for Fault Diagnosis
HV	High Voltage
ICT	Information & Communication Technologies
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IS	Information System
LSVPP	Large-Scale Virtual Power Plant
LV	Low Voltage
MAS	Multi-Agent System
MV	Medium Voltage
OLTC	On-Load Tap Changer
PKI	Public Key Infrastructure
RES	Renewable Energy Sources
SDM	Supply-Demand Matching
SGAD	Smart Grid Automation Device
SOA	Service Oriented Architecture
VPP	Virtual Power Plant
TSO	Transmission System Operator
TCP/IP	Transport Control Protocol / Internet Protocol
WWW	World Wide Web

Figure 21: EU project team at the CRISP field experiment site on the Swedish island of Öland.

CRISP project consortium (www.ecn.nl/crisp):

ECN, The Netherlands (www.ecn.nl)

ABB, Sweden (www.abb.com)

BTH, Sweden (www.bth.se)

EnerSearch AB, Sweden (www.enersearch.com)

E.ON, Sweden (www.eon.se)

IDEA, France (www.gie-idea.com)