Distributed Intelligence in Critical Infrastructures for Sustainable Power
ENK5-CT-2002-00673

Case study simulations and results
D1.8

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Document description

This document provides the main description, the results and the analysis of simulations done along the CRISP project. The goal is to summarize the information in order to give the main recommendations, expectations and conclusions for the design of the future distribution network architecture. The three aspects of market constraints, ICT requirements and EPS technical constraints are investigated.

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Acronyms and Abbreviations

Acronym	Means
ACE	Area control error
ACL	Agent Communication Langage
AGC	Automatic generation control
API	Application programming Interfaces
APX	Amsterdam Power eXchange
ATC	Available transfer capability
BA	Balancing authority
BO	Business Operations
BUSMOD	Business Modelling in a world of distributed generation
B2B	Business to Business
CBM	Capability benefit margin
CDI	Constrained Data Items
CHP	Combined Heat Power
CIM	Common Information Model
COP	Coefficient Of Performance
CPS	Control performance standard
CPU	Central Processing Unit
CRISP	Distributed Intelligence in CRitical Infrastructures for Sustainable Power
DCLM	Direct control load management
DCS	Disturbance control standard
DG	Distributed Generation or Dispersed Generation (similar to DR)
DG-RES	Distributed generation based on renewable energy systems
DMS	Distribution Management System
DNO	Distribution Network Operator
DNS	Domain Name Server
DoS	Denial of Service (security study)
DR	Distributed Resources (similar to DG)
DSM	Demand Side Management
EMS	Energy Management System
EPS	Electric Power System
FCI	Faulted Circuit Indicator
FDD	Fault Detection and Diagnostics
FPI	Fault Passage Indicator
GIG	Global Information Grid
GPS	Global Positioning System
GW	Gateway
HF	High Frequency
HV	High Voltage
HVAC	Heating Ventilation and Air Conditioning
HVDC	High Voltage Direct Current
ICT	Information and Communication Technology
IED	Intelligent Electronic Devices
IEEE	Institute of Electrotechnical and Electronics Engineers
IEC	International engineering consortium
IP	Internet Protocol
IPP	Independant power producer
IROL	Interconnection reliability operating limit
IVP	Integrity Validation Procedures
LAN	Local Area Networks
LN	Logical node
LPS	Lightweight Privilege Separation

LV	Low Voltage
LSVPP	Large scale virtual power plant
MAS	Multi Agent Systems
MOM	Means, Opportunity and Motif
MV	Medium Voltage
NBW	Network-Based Warfare
NRU	No Read Up
NWD	No Write Down
OASIS	Open access same time information service
OATT	Open access transmission tariff
OLTC	On Load Tap Changer
OSGi	Open Software Gateway initiative
PAM	Pulse Amplitude Modulation
PCC	Point of Common Coupling
PLC	Power Line Carrier
PMU	Phasor Measurement Unit
PNO	Power Net Operations
POD	Point of delivery
POR	Point of receipt
PPP	Point-to-Point Protocol
PQ	Power Quality
PS	Power System
PSTN	Public Switched Telephone Network
PTP	Point to point transmission service
PV	Photovoltaic
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RCIS	Reliability coordinator information system
RAS	Remedial action scheme
RES	Renewable Energy Systems
SCADA	Supervisory Control and Data Acquisition
SCL	Substation Configuration Langage
SDM	Supply and Demand Matching
SO	Services Operations
SVC	Static Var Compensator
SVG	Static Var Generator
TBS	Time Based Security
TCBR	Thyristor Controlled Braking Resistor
TCP	Transport Control Protocol
TRM	Transmission reliability margin
TSO	Transmission System Operator
TTC	Total transfer capability
UDI	Unconstrained Data Items
UML	Unified Model Langage
UVLS	Under Voltage Load Shedding
VPP	Virtual power plant
WAN	Wide Area Networks

Summary

This document summarises and extends the simulation results from the tools developed along the WP2. A combination of the partners view on the possible merge of ICT network and EPS in the future electrical architecture is illustrated through case studies.

The main scope is the distribution network which needs strong development in order to become more visible, more controllable. A difficulty describing the architecture is to identify exhaustively the actors and their level of responsibility in the correct running of the whole system.

The case studies highlight the expected system structure and the combination of the infrastructures.

A general overview on several aspects of the transmission and the distribution networks (technical operation, trading, securing, defence plan) and on several aspects of ICT improvement and risks has been given in previous work packages of the part 1 of CRISP project.

The approach is based on the study of chosen cases, allowing to interact and to present our works. The MV network, including of course the main HV/MV substation, has a specific position in our purpose: historical, technical and trading boundary between the transmission and the distribution system, involving new functions in the context of the future important dispersed generation participation. The whole electrical system is not yet ready to work properly with a lot of DG and DG-RES and in a new electrical deregulated market: the system required adapted information system that does not exist today, both for the market support and the MV application support. A large step in distribution automation need to need achieved.

The multiplication of actors (production, transmission, distribution, customers, local networks) caused by deregulation is an additional issue for planning and operating correctly the network.

The interactions expected between the low level of the network (distribution EPS, VPP, customers, small aggregators) and the high level of the network (transmission EPS, LSVPP, large aggregators) require to structure the system in various integrated levels, allowing the operators at each stage to manage efficiently the power flows for steady-state, transients and temporary electrical variations. Compared with the present SCADA situation, the ICT will allow the needed information to be shared by various tools and actors at various locations and will let the local intelligence to be developed in depth.

Simulation gives the main lines for the future development.

1. Introduction

The new kinds of architecture proposed in CRISP project deals at the same time with the deregulation of the electrical market and the massive insertion of DR in the network. The study of networks may change due to the future active interaction between transmission and distribution networks. Some existing functions activated in distribution for transmission (or rather global energy balance) need should be reinforced by intelligent and distributed controlled (or reactive) loads and production units. The document reports the main aspects of modelling and simulating a network composed of transmission and distribution parts. The summarized simulation results and conclusions are reported in this document and are mainly extracted from [D1.3].

The distribution electrical power system needs a great improvement in automation and information systems. The first real step needed is to be able to observe the network inside the feeders and the spurs, making and preparing data for local computations, a main first computation being the local load flow: circulation of power and current in the conductors, voltage variations on the different nodes, and the power loss evaluation in the network. Another important point is the automation of the protection system and of the fault diagnostic in the context of a new flexible MV grid operation. This point has been one of the objects of the simulation achieved during CRISP, especially for the experiment done in Grenoble.
The results of the software proposed for locating the fault are presented in this document. The impacts of loads and DR on the accuracy of the fault distance are quantified and analysed. The HTFD tool described in D1.4 and detailed in D2.3 has been tested for massive DR insertion.

.Several different forces drive a change in the current worldwide energy supply, production less on fossils reserves based and more oriented on electricity usage, with a larger distributed electricity generation. The growing share of DG in the electricity system may evolve in three distinct stages:

- **Accommodation.** Distributed generation is accommodated in the current market. Distributed units are running free, while centralized control of the networks remains in place.
- **Decentralization.** The share of DG increases. Virtual utilities optimize the services of decentralized providers through the use of common ICT-systems. Central monitoring and control is still needed.
- **Dispersal.** Distributed power takes over the electricity market. Local low-voltage network segments provide their own supply with limited exchange of energy with the rest of the network. The central network operator operates more like a coordinating agent between separate systems rather than controller of the system.

In specific parts of the world there are already signs of the decentralization stage. During the second and third stage of DG growth, the lower parts of the electricity grid are expected to evolve from a hierarchical top-down controlled structure into a network of networks, in which a vast number of system parts communicate with each other and influence each other. In this scenario, the standard paradigm of centralized control, which is used in the current electricity infrastructure, will no longer be sufficient. The number of system components actively involved in the coordination task will be huge. Centralized control of such a complex system will reach the limits of scalability, computational complexity and communication overhead.

The tools developed in WP2 are used for this document. Other simulations used during CRISP project are summarized and reported.

2. DG insertion on EPS: transmission and distribution

2.1 Introduction

A comprehensive study has been carried out on impacts for the transmission system with high level of insertion of DG on the distribution. For this purpose a model associating transmission area and distribution areas has been proposed and detailed in [D1.1] and [D1.3]. Several papers have been presented at different conferences in order to share the results with the scientific community [c1], [c2], [c3]. This chapter summarize the main information resulting from simulations done with Eurostag and focus on stability aspects in the EPS. Some specific aspects was developed in [D1.3] about intentional islanding in the distribution and are not reported here. For detailed information and description of the model, please refer to the chapter 3 of [D1.3].

2.2 Overview of the network model

The VHV (typically 400kV in Europe) network shown on the following figure 1 is typically meshed and is operated in order to work properly even if a failure occurs on one of the major component of the network (typical robustness rule called ‘n-1’, used today for the transmission devices and large power plant units).

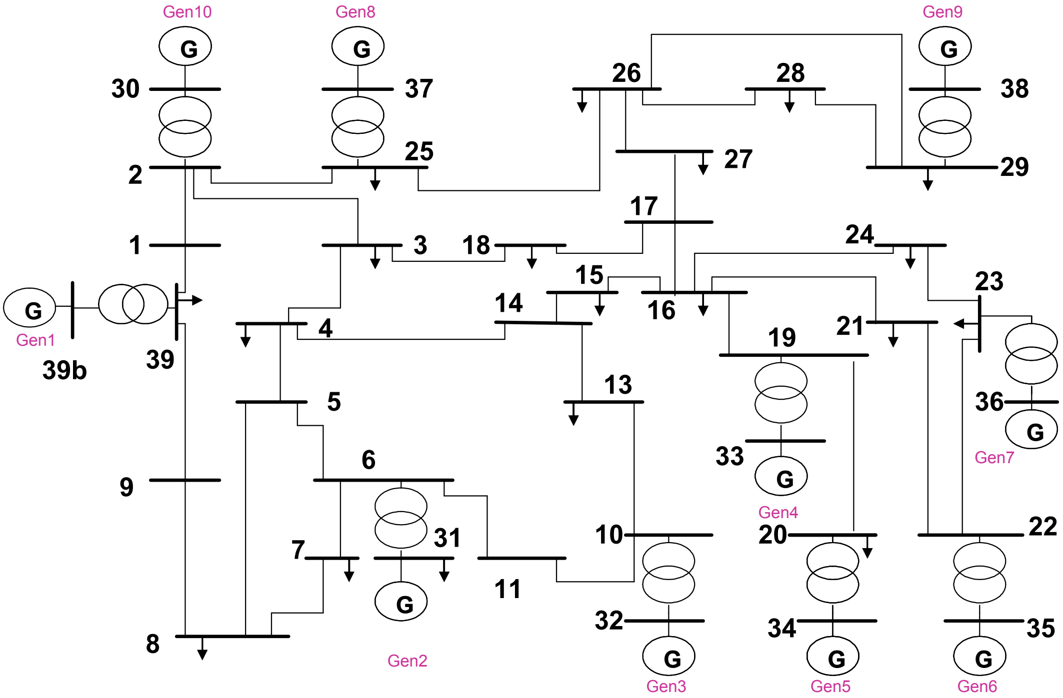


Figure 1: transmission network CRISP_39buses (VHV network)

HV loops (typically 63kV or 90kV in France) are derived from this network to supply HV/MV substations, the loop being connected to the same HV substation for the two ends, or being connected to two different HV substations. The following figure 2 shows an example with a HV loop installed between busses 11 and 13 of the VHV transmission network described above.

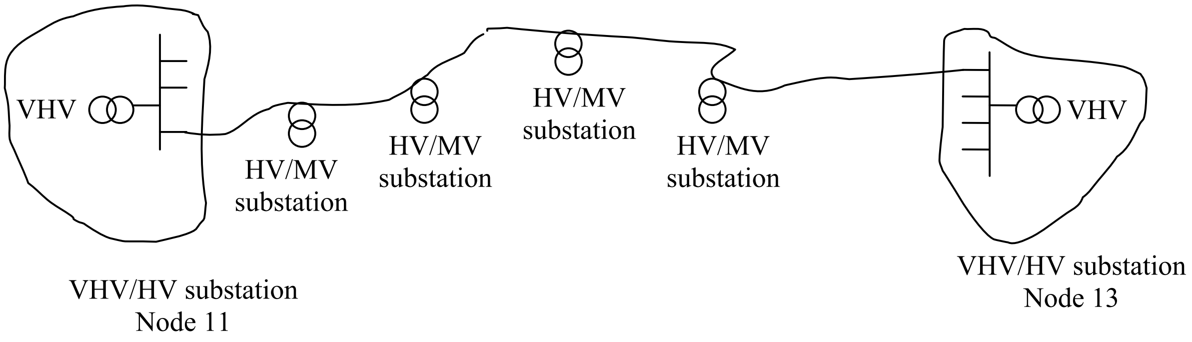


Figure 2: HV typical network with closed loop

The MV and LV networks are operated in radial mode in general (except for some large cities in the world). Our simulations were focus on MV areas, the LV areas being aggregated for demand and production modelling. The following figure 3 illustrates a case that has been studied.

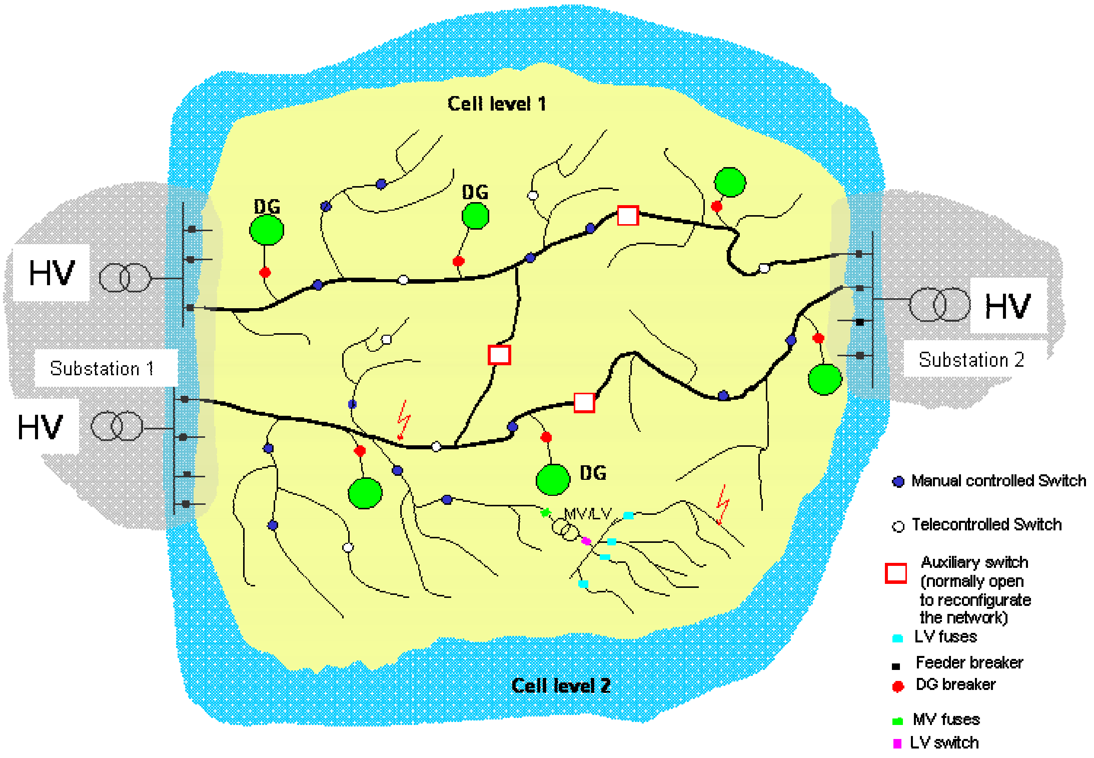


Figure 3: MV typical network operated in open loop

2.3 Main results of simulation

The occurrence of short-circuit in a transmission line is a critical event in the case of large insertion of DG in distribution, due to the large impact (in term of area and also deepness of the associated voltage dip) on the voltage. The critical consequence is a massive and synchronized disconnection of production induced by loss-of-mains protections or internal generation protections. If the disconnecting protection is designed adequately to support the system in this event case, the robustness is hardly reinforced: the main technical solution being developed in this direction worldwide is the called ‘ride through capacity’, allowing the operator to recover the main part of the DG production after the normal fault clearing of the short-circuited line. In general these lines are directly connected from a VHV substation to another VHV substation, so the elimination of a line should involve few changes in the demand – production balance (some changes occurs in the load flow resulting caused by production tripping and load tripping). If this event entails some local critical changes in the load flow, the possible future development of 'network supporting capacity' by DG (contribution to ancillary services) should prevent the local system from instability issue. The robustness evaluation depends a lot of the assumption of the types of DG involved (what control means, what protections installed)!

In case of development of 'network supporting capacity' by DG contributing to primary reserve and to the mitigation of power oscillations (see intelligent load shedding and smooth load relief approach in [D1.5]), the existing robustness is kept and should be locally reinforced, allowing a massive insertion of DG. The ultimate assumption in the way of distribution automation is to develop autonomous capacity for a lot of MV cells, improving drastically the total robustness by the stability induced area by area at distribution level.
The cascading outage caused by over-current in the VHV lines is naturally prevented by the DG insertion. The transmission system is less loaded with a high distributed DG insertion and so the overloads caused in the system after a loss of lines is less important. This is an important conclusion because the incidents caused by overloads were detected in the last blackouts occurring in Europe or in the USA.

The frequency deviations caused by the load variation and generation variations are critical if the system does not have enough resources to compensate the active power and ensure a good voltage profile. The question of DG contribution for this frequency control is crucial in case of high DG insertion. The reliability aspect is not the same for units contributing to the reserves in the system: the loss of an 'active' DG unit is not important compared with the loss of a large power plant unit (several hundred of MVA lost and a few tens of MVA of active power reserve). If the loss of this DG unit is singular and caused by internal failure, there is a weak impact on the system balance. Nevertheless if an event (as short-circuit on VHV not properly and quickly cleared) consequence is the tripping of a large amount of 'active' DG units, the stability issue is observed.

The participation of DG to the local voltage control should decrease the injected reactive power from the transmission system to the distribution system and so, the influence during voltage collapse phenomena would be improved. However, this voltage collapse phenomena is a complicated event and nothing general could be said in this report. The control of DG may take into account some reactive power local balance, contributing to a correct distributed voltage control. In the view of CRISP MV cells (level 1 and level 2 as described in [D1.4] and [D1.7]), the voltage control among the MV network should be mainly managed by the agent of MV cell level 2.
The loss of synchronism of different generators depends on the configuration of the system. Special attention should be paid in the connection step (location and tuning of regulators) of DG in order to meet some global system stability criteria. The dynamical model for synchronous machine is important in this kind of studies.

The crucial problem relative to the DG insertion rate is the synchronization of the disconnection or of the connection following a large power trouble in the transmission system. If this constraint is not at all controlled or limited, the effect on the large power plants controls is obvious. Now assuming that a part of the DG units (20% of the most important DG units that may contribute to nearly 80% of the DG total production) contribute to the frequency and voltage stability, assuming that dedicated ICT at distribution level allow the operators to limit the power fast variations among the VHV network (by production control or load control as described in [D1.5] or in [D1.7]), the synchronization problem may be avoided.

2.4 Additional comments relative to critical events measured

The European VHV network is very large and has natural structured area with the different countries. The principle of mutual help is running up to a certain level of electrical trouble, contributing to an accepted level of robustness at the level of UCTE (the large interconnected network). When a country is facing too much trouble entailing a cascading effect on the lines of its boundaries, this country is quickly isolated from the others. This kind of selectivity was not taken into account in the CRISP proposed network model. It may be interesting in future extended work to develop a benchmark more representative of this European capacity with decoupled area.

The blackout that occurred in Italy on September 2003 is an interesting example because the variation of power balance was near 6GW (the total fast reserve expected in Europe is near 3GW). This large variation explains the high difficulty of avoiding the blackout in Italy with an internal missing power of 6GW. The extra produced power in Europe involved a temporary over-voltage and over-frequency after the separation from the Italy. The maximum frequency observed in Europe (outside of the blackout area) was near 50.3Hz during a few seconds (in Hungary) just after the disconnection from Italy, and the frequency was kept near 50.25Hz during tens of seconds before returning back to 50Hz following large reduction of production in France and Germany (near 6GW). The over-voltage after isolation from the Italy was kept under 110% of the nominal voltage. Just before the separation, the Hungary observed a low voltage under 85% of the nominal voltage during 1s. From the load flow through the UCTE network, it is expected that the voltage level just before the isolation from Italy was higher in Germany and in France (where was located the main production). Taking into account the existing thresholds for the disconnecting protections of the DG, the large majority of the DG production was maintained in Europe during this critical event (of course the DG units located in Italy tripped massively due to local huge variation of voltage in amplitude and in frequency). In the same electrical situation (load flow), but with many more DG installed (in %) all around the Europe during this phenomena, the resulting impact depends on the real reserve existing during the trouble. A best way should be that the fast reserve is not concentrated in a few large power plants, but is distributed and shared with the main DG units of the network.

ICT becomes necessary to manage locally the time allocation for the power reserves, cell by cell. If contributing to the primary control is focus on (just fast reserve to support the system), a simple time curve of the support may be defined: time response of nearly 1s associated with a droop characteristic (frequency/power produced) limited at 3% of the power capacity installed (for instance and depending on the type of DG involved), recovering the previous power produced with a time response of a few minutes. In order to keep existing stability settings in the large power plants, a dead-band of around 100mHz may be defined for the response of the DG production contributing to this primary control.

This dead-band let the large power plants dealing with the normal power variation in the system (time variation of the loads and production units), and makes react the ‘active’ DG when power variation becomes very large (more than 50.1Hz or less than 49.9Hz), see on figure 4.

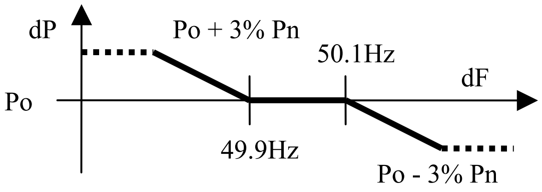


Figure 4: dead-band and droop frequency support by ‘active’ DG

Another interesting example is relative to the blackout that occurred in Sweden and in Denmark during September 2003. The condition is not the same as the case of Italy since the associated interconnected network is not synchronized with the UCTE (some back-to-back DC interconnections with UCTE): the network is weaker and more sensitive to strong events (loss of lines or loss of large generating unit). During the double busbar fault occurring in the south of Sweden, that lead to the blackout of the south and of the eastern part of Denmark, some measurements were recorded in Stockholm where the power was successfully maintained.

These data show that the frequency fell under 49.5Hz during 8s just after the occurrence of the fault, and that the voltage fell under 85% of the nominal voltage during 5s nearly 90s after the occurrence of the fault in the south. Taking into account the thresholds of the DG already installed in the distribution, the main part of the DG may have been tripped by the disconnecting protection. In this case the DG insertion may impact more drastically the stability of the transmission system. The solution for avoiding restriction is developing a less sensitive protection for the DG (allowing some support capacity for the system) and also developing some capacity of extra power contribution (with a same relative level of nearly 3% of local reserve by unit).

2.5 Conclusion

The proposed model for transmission has been simulated with different rate of insertion of DG. The DG impacts during major events such as short-circuits, frequency deviation, line tripping or voltage collapse has been studied. A methodology to study the robustness of the EPS has been proposed in [D1.3] and has been used for the simulations. This methodology leads to the evaluation of a robustness index in case of appearance of selected contingencies. It was applied to a test case in order to survey the influence of DG during disturbances and to fix criteria to limit the DG insertion in the EPS.

These limits were established taking into account different scenarios for DG dynamical characteristics. In general terms, the DG disconnection protection and the intermittence are the main roots of potential problems for the whole system. With the assumption of a low control of the installed DG and with no change on the thresholds of the disconnecting protection, a reduced amount of DG penetration seems to be more appropriated for a low risk level operation. On other hand, new control strategies such as the DG participation to the ancillary services or the intentional islanding could constitute future tools to increase the system robustness, notably to counteract total blackouts.

The analysis of the appropriate rate of DG in the distribution must take into account the real or expected level of control of this DG (including the various aspects of grid and internal generation protections).

It is still difficult to give a clear value of limited rate for DG insertion: this technical limitation is highly dependant on the system analysed (extension of the voltage trouble due to critical fault among the interconnected system), on the real distribution of the DG inside the whole interconnected network and on the performance expected for the DG control and protections.

3. EPS Fault diagnosis on MV network: software accuracy

3.1 Introduction

This important function of distribution automation has been experimented with a focus on the ICT characteristics. The experimentation deals with fault detection, fault localization, including specific fault distance evaluation, fault isolation, partial restoration and finally reset and update of the real time situation. The following results in this document, based on various simulations performed on the Fault Diagnostic MV network, give the electrical limitation of such a distance evaluation algorithm with the connection of a large amount of local production.

This is a critical point when combining EPS and ICT approach. The risk of fault distance evaluation leads to a risk of bad or absurd value injected in the Fault Diagnostic algorithm, leading thus to possible wrong switching operation on the EPS area or also to fatal error in the local program (core dumped) making aborted the running local control.

Another aspect is the accuracy of the needed transmitted data, knowing that various errors are chained. Defining the required accuracy for metering, converting data and transmitting data (following an analogical to digital conversion) depends on the final error required and also in the performance of the analysing program (HTFD code described in WP2.3 and used for experimentation in WP3.2B in our case study).

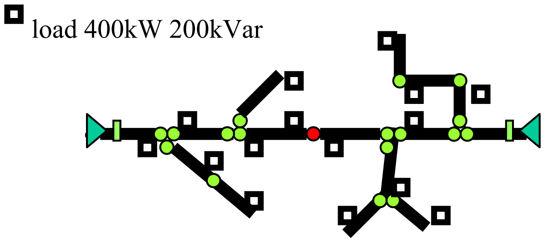


Figure 5: MV level 1 cell used for HTFD tool

The case study includes a simple MV level 1 cell with two main supplies. The load distribution is presented on figure 5.

The targeted MV level 1 cell, lead by the local agent, includes FPI, EPS switches, DG and DG-RES. The following figure 6 recalls the location of the FPI and EPS switches.

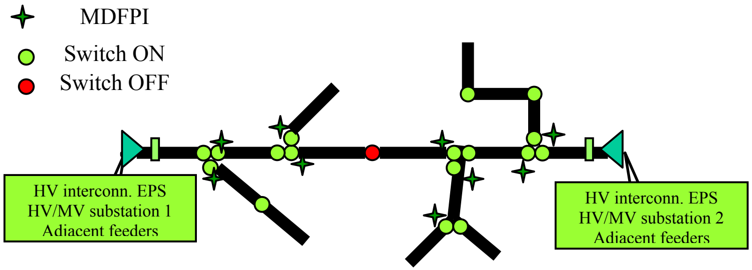


Figure 6: FPI ICT components distributed in the simulated cell

Since the object is to analyse the error on fault distance evaluation (in order to have finally a better information analysis for the local agent), we will focus on a single configuration extracted from the previous figure with only one input as illustrated in figure 7.

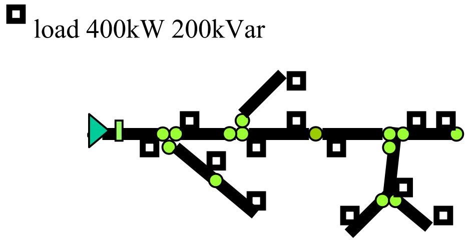


Figure 7: simplified single feeder for distance evaluation error

Arene simulator (not in its real time version but quite similar) has been used for this purpose. The network is represented as indicated in the following figure 8. The single-line diagram is identical to the representation with Arene real time, as it uses the same graphical pre-processor. Faults are distributed on the points were an arrow with a number is shown.

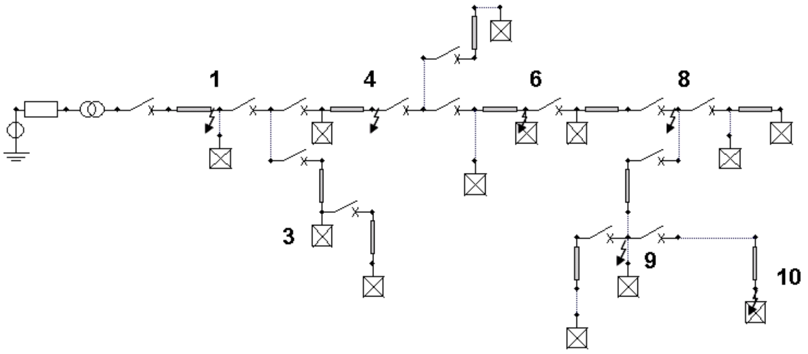


Figure 8: Arene model and fault locations tested

Main characteristics of this simplified distribution network

The short-circuit power (three-phase short-circuit current multiplied by the nominal voltage and also by the square root of three) of the main source on secondary side is 180MVA (the maximum short-circuit current expected is nearly 5kA).

The part of network chosen is designed as a 7MVA feeder, which has a total length of 55km, lines or cables. All the conductors have a length of 5 km, and the 13 distributed loads are 445kVA as in the initial CRISP MV cell model, with power factor of 0.9. A brief description of the grid is given in the next table:

Table 1: Network parameters

Network part	**Direct Resistance**	**Direct Reactance**
Up Network	$R_{dRT} = 0.0266\Omega$	$X_{dRT} = 0.3989\,\Omega$
Transformer, 36MVA,63kV/20kV	$R_{dTR} = 0.0463\Omega$	$X_{dTR} = 1.664\Omega$
Lines	$R_{dL} = 0.2\Omega/km$	$X_{dL} = 0.299\Omega/km$
Cables	$R_{dC} = 0.203\Omega/km$	$X_{dC} = 0.1256\Omega/km$
Load	$R_{CH} = 2400\Omega$	$L_{CH} = 3.820H$

3.2 Fault localization method

The method used for fault distance computation is based on the current measured at the sending-end (secondary side) of the HV/MV power transformer (various methods are presented in [a1]). This fault current is classified as three-phase, two-phase or single-phase fault. The RMS (root mean square) value is evaluated and averaged, and then gradually identified as equivalent impedance section by section. On the next figure 9, a simplified scheme shows the fault situation, and a following equation gives the principle of the method.

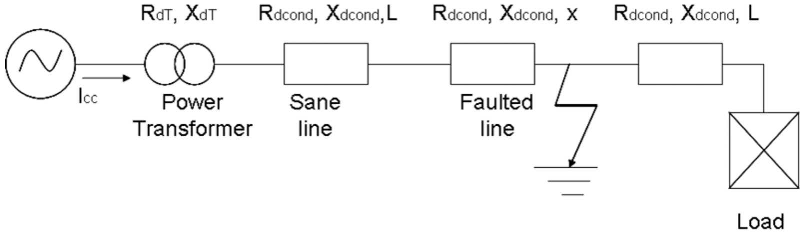


Figure 9: Simplified fault network scheme

The main equation for fault distance computation is:

$$(Rd_T + L.Rd_{cond} + x.Rd_{cond})^2 + (Xd_T + L.Xd_{cond} + x.Xd_{cond})^2 = k\left(\frac{U}{\sqrt{3}Icc}\right)^2$$

With *k –coefficient, depending on the type of fault, k=1, for a three phase fault, k=0.75 for a phase to phase fault.*

Such a one-end method is precise enough since the considered currents are high, compared with the load ones. A passive distribution 'RL' load can be considered as an open circuit for the three and double phase fault currents. The contact impedance between phases is considered to be zero. The method needs no additional changes to work properly for distribution networks with many taps. It is suitable for permanent faults, since the variables are expressed at the fundamental frequency.

3.3 Generation model

The DR contribution when faults occur may disturb the localization accuracy. This effect is studied for some cases, specifically for distributed synchronous machines. A typical 0.4MVA Diesel Generator has been simulated. Normally there are three possible connections between a production mean and the network grid: induction machine, synchronous machine and power electronics (inverter). The power electronic devices are "smart" devices – they have a control loop that is very fast and does not allow high currents. The induction machines are rapidly demagnetized by the voltage drop and not really able to provide a really high contribution to the permanent fault after a few cycles. Synchronous generators are more independent since they have their own excitation like permanent magnets or excitation circuit. That makes this type of generators the most “dangerous” in terms of fault current contribution and so the most suitable if one wants to study the DG effect on the fault location. Synchronous generators directly connected to the distribution grid are mostly hydro turbines. Their behaviour is similar to that of a diesel generator, but the last is more rapid in terms of reaction. So that kind of generator is chosen for the representation of the worst case of reaction to a fault. Here next is shown a simplified scheme of the used generator on figure 10:

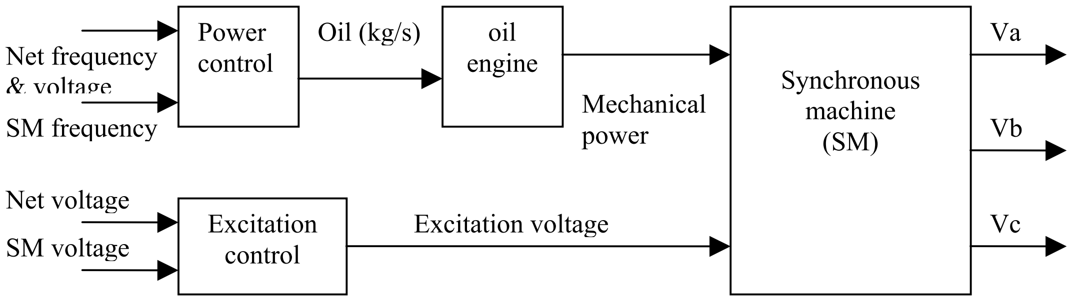


Figure 10: Diesel Generator or oil engine

The excitation block is an IEEE standard Type 1 excitation, which description can be found in [a2]. The Diesel engine model is developed and validated according to [a2]. The machine has 10% speed droop (when islanded at starting phase or in intentional islanded mode), and 400V controlled at the output in case of islanded mode. The grid connection power transformer is Wye-Delta coupled.

During normal state in interconnected mode, active power and reactive power are following a reference thanks to oil injection control and excitation current control. When the fault occurs, there is a combination between the excitation system and the inherent characteristics of the machine. For instance a voltage drop of 20% (remote short-circuit down in the feeder) should be compensated by the excitation (the current is increased to keep the same active power in the point of common coupling with the grid). A direct short-circuit at the point of common coupling involves a clear current limitation by the internal impedances.

3.4 DR impact on fault location

In this section, the simulation study with DR impact is described for a typical case. In order to explain the theoretical problem, the study is simplified as illustrated on the next figure 11 with a main source and one DR synchronous machine:

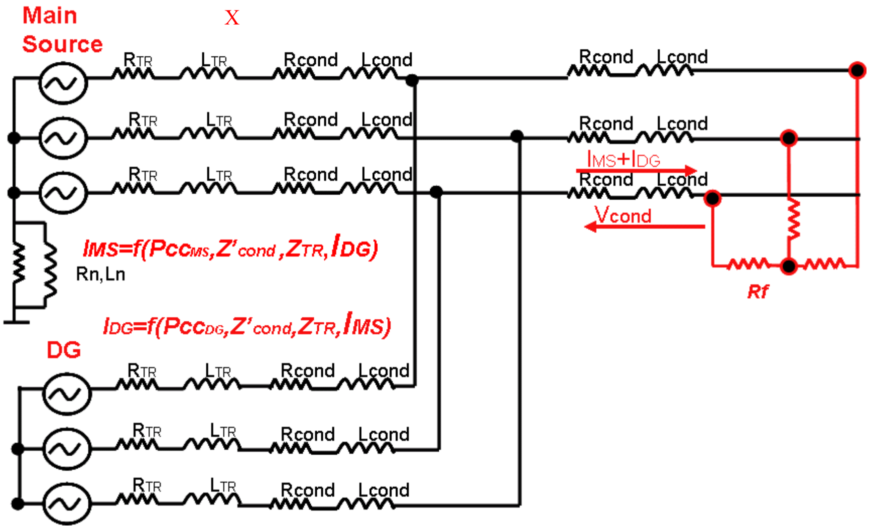


Figure 11: Theoretical situation for a three phase fault on network with DG

The length X of the public network on the path between the main source and the fault (Rf) is ended at the point of common coupling with the derivation including the DR. This parameter X is variable with the fault distance. For a three phase fault the KVL equations are:

$$\begin{cases} V_{MS} = (Zd\_tr_{MS} + Zd_{MS}.L_{MS}).I_{MS} + (I_{DG} + I_{MS}).ZdcommX \\ V_{DG} = (Zd\_tr_{DG} + Zd_{DG}.L_{DG}).I_{DG} + (I_{DG} + I_{MS}).ZdcommX \\ Rf = 0 \end{cases}$$

Rearranging the equation with respect to X yields:

$$X = \frac{1}{Zdcomm}.\frac{(Zd\_tr_{DG} + Zd_{DG}.L_{DG})((Zd\_tr_{MS} + Zd_{MS}.L_{MS})I_{MS} - V_{MS})}{V_{MS} - V_{DG} - (Zd\_tr_{MS} + Zd_{MS}.L_{MS} + Zd\_tr_{DG} + Zd_{DG}.L_{DG})I_{MS}}$$

meaning that a measurement of the fault current on the substation should be sufficient to find the fault location. However for the purposes of this study the formula is to be used as is (1), without taking into account the DR contribution.

For a two-phase fault, considering the phase to phase voltages, the fault distance is the following:

$$X = \frac{1}{Zdcomm}.\frac{(Zd\_tr_{DG} + Zd_{DG}.L_{DG})(U_{MS} - 2(Zd\_tr_{MS} + Zd_{MS}.L_{MS})I_{MS})}{U_{DG} + 2(Zd\_tr_{MS} + Zd_{MS}.L_{MS} + Zd\_tr_{DG} + Zd_{DG}.L_{DG})I_{MS} - U_{MS}}$$

Since for phase-to-phase faults the fault currents are not totally identical, a mean absolute value has been taken for the fault distance calculation. Once again it should be noticed that the fault location is going to be found by applying the original formula in order to evaluate the DR impact.

3.5 Fault simulations and locating results

The simulation study has been carried on following three main criteria:

- The fault position in respect to the generators
- The short circuit power of the DR
- The DR distribution over the network

The simulations were performed in following manners:

1. generator on point 6 and various fault locations with given DR power injection,
2. generator on point 6 and various fault locations with various DR power injections,
3. Two generators on point 6 and point 3 (same total power) and various fault locations

3.5.1 Three -phase faults

Table 2 presents the results obtained for the reference case study without any DR or any load: the software gives the expected evaluation for the distance. Arene real time provides adequate results with a time step of 50µs (error less than 0.5%). With increased time step of 1.2ms, due to the high number of real time calculations and external data exchanges, the accuracy is reduced: less than 3.5% error. The transmitted current value is coded on 8bits, involving a current step of nearly 25Amps, meaning nearly +/-2.5% error for 1000A expected.

Table 2: Simulation with cables, 0DR and no load (theory, HTFD, Arene)

Fault Loc.	Dist. Ref. (km)	Fault current Theory > HTFD (A)	Evalua. HTFD Distance (km) err.<0.1%	Fault current Arene (A) dt 50µs	Error With Arene (%) dt 50µs	Fault current Arene (A) dt 1.2ms	Error With Arene (%) dt 1.2ms
	0	5596	0	5591	-0.09	5463	-2.38
1	5	3979	5	3975	-0.10	3845	-3.37

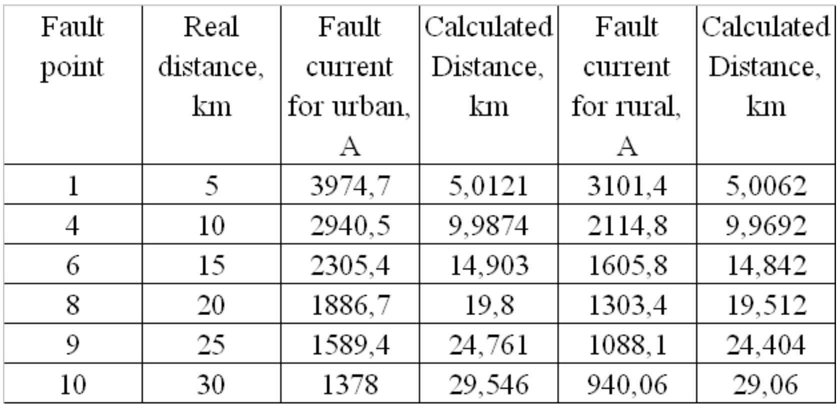
4	10	2939	10	2936	-0.10	2882	-1.94
6	15	2295.5	15	2291	-0.20	2215	-3.51
8	20	1873	20	1869	-0.21	1813	-3.20
9	25	1577.5	25	1573	-0.28	1526	-3.26
10	30	1361	30	1355	-0.44	1318	-3.16

Table 3: Simulation results with cables, 0DR and load (Arene)

Fault Location	Distance reference (km)	Fault current Arene (A) ref. dt 50µs	Fault current Arene (A) dt 1.2ms	Error With Arene (%) / ref. dt 1.2ms
	0	5591	5441	-2.68
1	5	3975	3840	-3.40
4	10	2941	2884	-1.94
6	15	2305	2230	-3.25
8	20	1891	1830	-3.23
9	25	1605	1555	-3.11
10	30	1397	1353	-3.15

The table 4 shows the impact of DR located in the middle of the distribution network on the expected accuracy of the computed distance evaluation. Urban means in this table that the network is composed of cables, and rural means it is composed of lines. The current measured and the localization programs are combined for the results, showing the difference obtained between the exact location of fault (real distance) and the evaluated distance (for urban or rural network). The accuracy is illustrated in the following Figure 8. As illustrated in the Figure 9, the DR compensates the errors induced by the distributed loads.

Table 4: Simulation results with 1DR 400kVA in point 6 and load



Fault point	Real distance, km	Fault current for urban, A	Calculated Distance, km	Fault current for rural, A	Calculated Distance, km
1	5	3974,7	5,0121	3101,4	5,0062
4	10	2940,5	9,9874	2114,8	9,9692
6	15	2305,4	14,903	1605,8	14,842
8	20	1886,7	19,8	1303,4	19,512
9	25	1589,4	24,761	1088,1	24,404
10	30	1378	29,546	940,06	29,06

On the next figure 12 the computational error is shown:

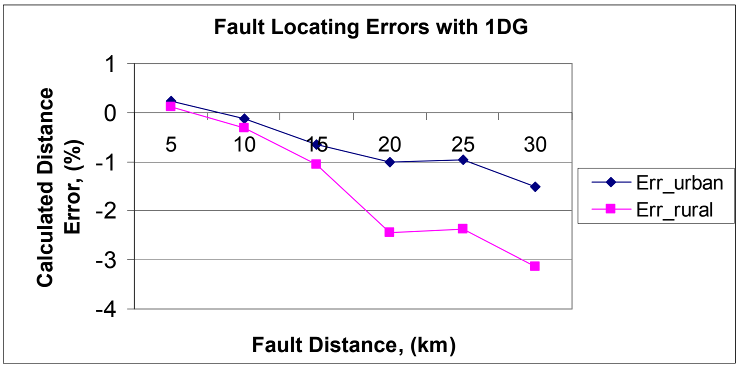


Figure 12: Fault Location Error

where the error is calculated as:

$$\varepsilon = \frac{D_{calculated} - D_{real}}{D_{real}}.100$$

As it could be seen the error in fault location is relatively small. The error is increased after the 15-th km, when the DR has a common path with the main source. The DR provides some fault current that decreases that of the main source. The computed fault distance is thus increased. For a better illustration the errors when there is no DR in the network being rural or urban, are shown on the next figure 13:

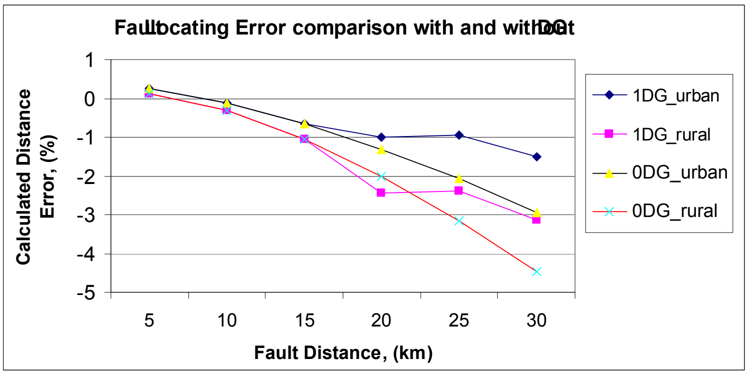


Figure 13: Fault location error comparison

The computed distance error is reduced due to the DR. Its influence is stronger with the shared network path. The “correction” is in the range of 2%. However this situation changes when the DR short-circuit power is bigger. On the next figure 14 the results for different DR powers (and thus short-circuit power) are shown. The DR power was increased by connecting other DR of the same size to the same connection point 6. For this type of connection is more realistic than a greater source, the “green” generators are not supposed to be small units [a12]:

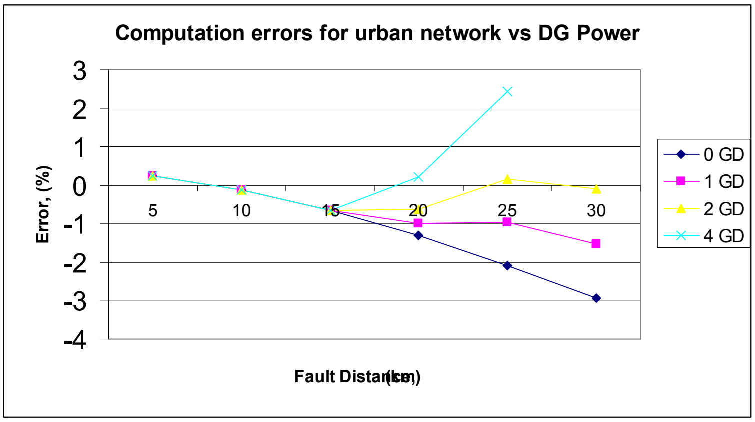


Figure 14: DR Power influence for urban network

Each added DR increases the calculated fault distance after the 15-th km. The locating error is smaller when 2DR are connected but when they double the error is increased to positive and for the 30km the obtained distance is greater than that of the network and no solution is found. Four DR is the worst situation for the presented fault locating results, which remain however acceptable, with an error of 3-5% maximum. Such a DR connection is very seldom, to say not realistic for the moment, the generated power is too much for the network. On the next figure 15 the results for a rural type of network are shown:

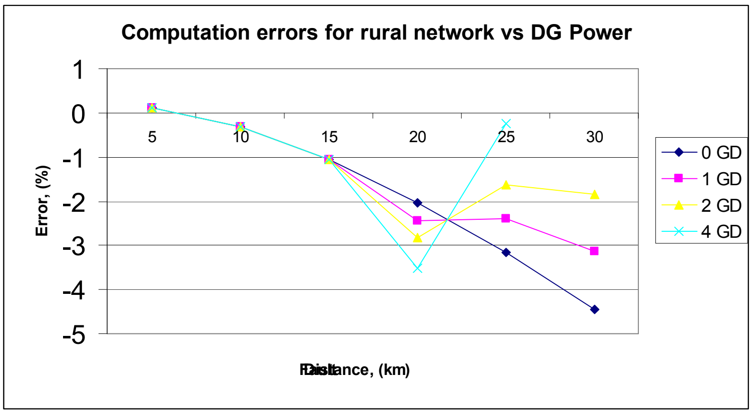


Figure 15: Error for a rural type of network

The results here are more pessimistic. The maximum error without DR is 4.3% whereas it is about 3% for the urban grid. The difference is result of the smaller cable reactance which increases the fault current. The load effect of the bifurcations upstream to the fault position is thus reduced in urban network. The DR decreases the error. However on the 20km fault point next to the DR, the influence is negative.

The case of two generators connected at two different points shows the influence of their distribution over the network for the same fault. The next figure 16 illustrates this phenomenon:

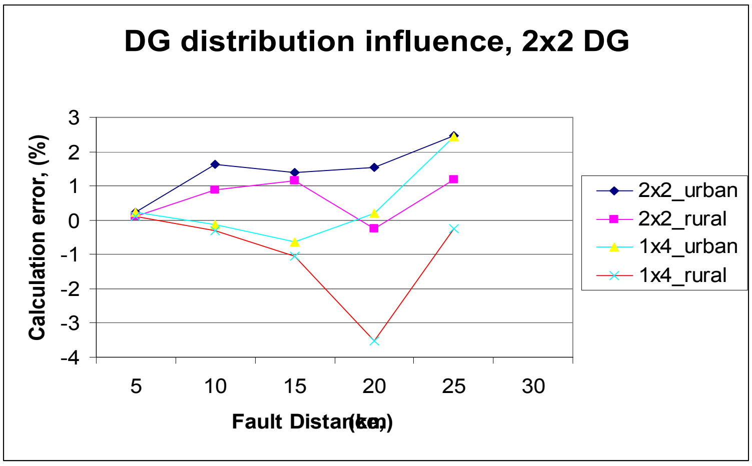


Figure 16: DR dispersion influence

Obviously the error is depending on the network type urban or rural. As it could be seen the DR dispersion on the network increases the error, due to the fact that they stand on the two ends of the network and deliver fault current for nearly all fault positions. But downstream the second DR group, the error is greater than it is for one DR group of equal power connected on the same place. That is due to the longer path shared by the first DR group and the main source which induces a smaller fault current from the last one. So the worst place for fault location remains the 30km where the two DR groups deliver both fault currents.

3.5.2 Two -phase faults

The same studies were performed for two-phase faults. On the next figure 17, results for the first case study are shown:

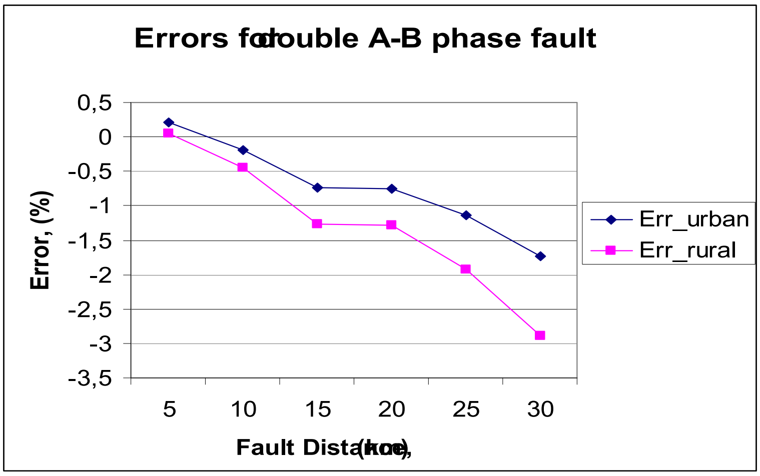


Figure 17: Errors in fault distance computation for double fault

The computed distance decreases with the fault distance. The range is the same as previously for the three phase faults. The point of 15 km is special because there is a DR connected. As previously mentioned, the DG fault current maintains the calculated distance in the vicinity of the fault but its influence is limited up to 10 km downstream. The DR power increase has an influence on fault location in urban network as follows on figure 18:

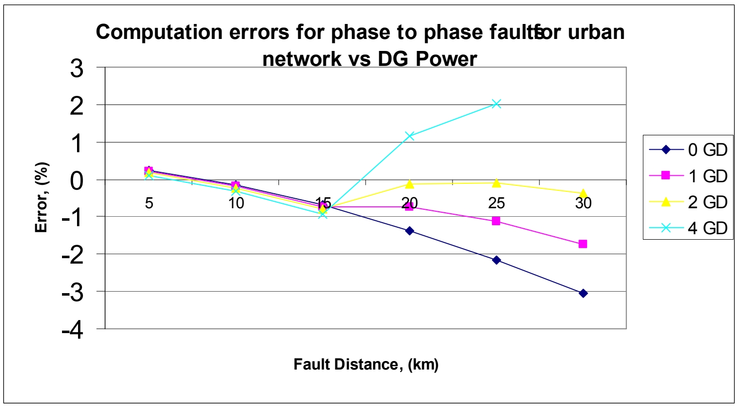


Figure 18: Results for urban network

The effect is greater for a double phase fault. It modifies the results even before the connection point, where DR and main source have no shared path. That is because they remain “connected” by the third safe phase. Its current induces some voltage on the two faulted phases. The DR insertion increases this voltage. Next figure 19 are depicted the results for a rural network:

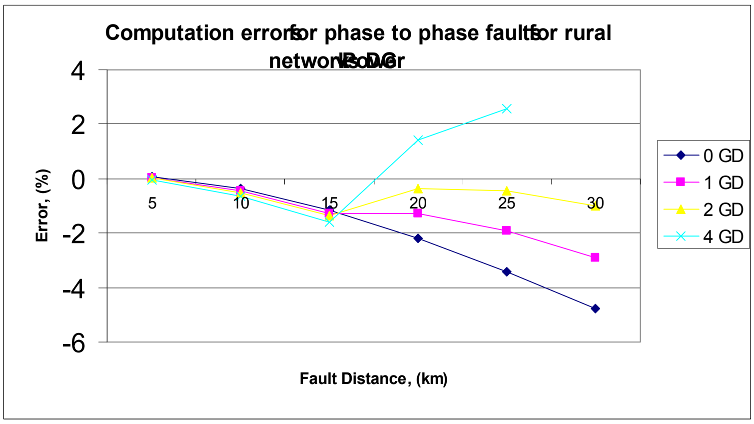


Figure 19: Results for rural network

As previously mentioned the error is greater but the tendencies remain the same.

The influence of the DR distribution on the fault location is visualized on the next figure 20:

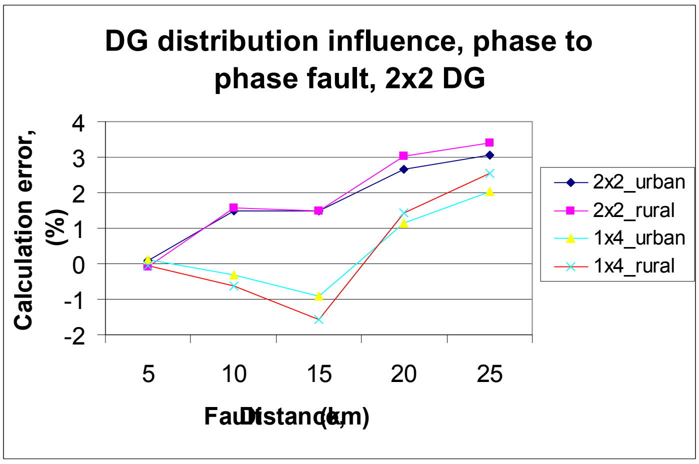


Figure 20: DR dispersion influence

The fault location results are similar to those obtained for three phase faults. The DR distribution increases the error. This effect is reduced when the fault is too far from the DR but their influence remains important.

3.6 Conclusion

Results for fault location of two-phase or three-phase faults in distribution network containing Distributed Resources are presented. A method based on one end data is applied. The DR influence is depicted and commented: it is relatively small. The DR distribution over the network increases the fault location error, since this implements a greater network path to be shared with the main source. Reducing their effect seems to be possible by connecting them at one point, which is preferably to be at the feeder, or they should have a dedicated feeder. The network type, urban or rural, impact is also studied and shows better results for smaller cable impedances which induce a greater fault current and so reduce the load effect.

The communication system based on measurements at the main substation (HV/MV transformers) on the sending-end feeders, and on the information by the FPI distributed in the system is still enough sufficient for the targeted application, even in the case of a massive introduction of DR in the network.

The reduction of accuracy in the distance evaluation is a problem when the fault occurs near a controlled switch, not equipped with FPI. For such uncertainties the information system has to integrate a level of confidence on the fault location (for instance red area for 20% of sections around an EPS switch). In case of uncertainty, the agent is informed of the risk of a new reclosing on fault and of the next proposed operation in this case.

4. Supply Demand Matching simulations

4.1 Market mechanism at local scale: the PowerMatcher

4.1.1 Multi-agent Systems for power management

4.1.1.1 ICT -Requirements

As a result of the electricity evolution as described above, the electricity infrastructure will get more and more inter-linked with ICT-infrastructure. The architecture and algorithmics of this ICT-infrastructure must be adapted to the technical structure of the (future) electricity net and the connected producing and consuming installations, but also to the structure of the liberalized energy market. This ICT-architecture and associated algorithms must be designed using a strong system-wide viewpoint, but must also consider stakes of local actors in the system. In other words, there is a need for a multi-actor coordination system, which optimizes global system objectives (like stability, power quality, and security of supply), in coherence with the interests of local actors in the form of installations for electricity production, consumption, and storage. These local actors vary greatly in characteristics defined by process type, purpose and size, and so do their specific constraints and objectives.
The resulting requirements of the ICT-infrastructure needed for the expected electricity evolution are:

- The ICT-architecture must be flexible, open and extensible.
- The coordination system must exceed boundaries of ownership. The total system includes the electricity network itself, central and distributed generators, electricity storage systems and electricity consuming systems. These system parts are owned by a vast number of parties, varying from public authorities, via companies, to private individuals.
- In this multi-actor system the stakes on the global level as well as those of individual actors must be taken into account. Control of distributed generators, electricity consuming installations and electricity storage, needs to be based on local information specific for the purpose and characteristics of the device. The power to take decisions on local issues must stay with each individual local actor.
- In a liberalized market setting, control (and local decisions) must be based on economical grounds.
- Communication between system parts must be uniformed and stripped from all local information. This is needed to reach the required flexibility and openness as stated in the first point, but also for reasons of privacy and trade secrecy.

Naturally, the total resulting system (the electricity infrastructure plus the ICT infrastructure) must be dependable, since the power grid is a critical asset in the modern society. Most developed countries currently have a highly dependable electricity supply, and any changes to the system must not weaken it but rather strengthen it. Further, the system must be secure, i.e. hardened against hackers and cheaters.

4.1.1.2 Meeting the requirements

Multi-agent systems (MAS) and electronic (virtual) markets provide the key technology necessary to meet the ICT requirements as described in the previous paragraph, for the following reasons:

- In multi-agent systems a large number of actors are able to interact, in competition or in cooperation. Local agents focus on the interests of local sub-systems and influence the whole system via negotiations with other software agents. While the complexity of an individual agent can be low, the intelligence level of the global system is high.
- Multi-agent systems implement distributed decision-making systems in an open, flexible and extensible way. Communications between actors can be minimized to a generic and uniform information exchange.
- By combining multi-agent systems with micro-economic principles, coordination using economic parameters becomes possible. This opens the possibility for the distributed coordination process to exceed boundaries of ownership. The local agent can be adjusted by the local stakeholder, and does not fall under the rules and conditions of a central authority.

- Using electronic markets a *Pareto efficient* system emerges, i.e. a system that optimizes on a global level, while at the local level the interests of all individual actors are optimally balanced against each other.

4.1.2 PowerMatcher

4.1.2.1 Basic concept

The PowerMatcher is a market-based control concept for supply and demand matching (SDM) in electricity networks with a high share of distributed generation. SDM is concerned with optimally using the possibilities of electricity producing and consuming devices to alter their operation in order to increase the over-all match between electricity production and consumption. In the PowerMatcher method each device is represented by a control agent, which tries to operate the process associated with the device in an economical optimal way. The electricity consumed or produced by the device is bought, respectively sold, by the device agent on an electronic exchange market [b6].

The electronic market is implemented in a distributed manner via a tree-structure of so-called *SD-Matchers*, as depicted in Figure 21. An SD-Matcher matches demand and supply of a cluster of devices directly below it. The SD-Matcher in the root of the tree performs the price-forming process; those at intermediate levels aggregate the demand functions of the devices below them. An SD-Matcher cannot tell whether the instances below it are device agents or intermediate SD-Matchers, since the communication interface of these are equal. The root SD-Matcher has one or more associated market mechanism definitions, which define the characteristics of the markets, such as the *time slot length,* the *time horizon*, and a definition of the *execution event* (e.g. “every whole quarter of an hour”, “every day at twelve o’ clock”). When an execution event occurs, the root SD-Matcher sends a request to all directly connected agents to deliver their bids. The device bids are aggregated at the intermediate matchers and passed on up-wards. The root SD-Matcher determines the equilibrium price, which is communicated back to the devices. From the market price and their own bid function each device agent can determine the power allocated to the device.

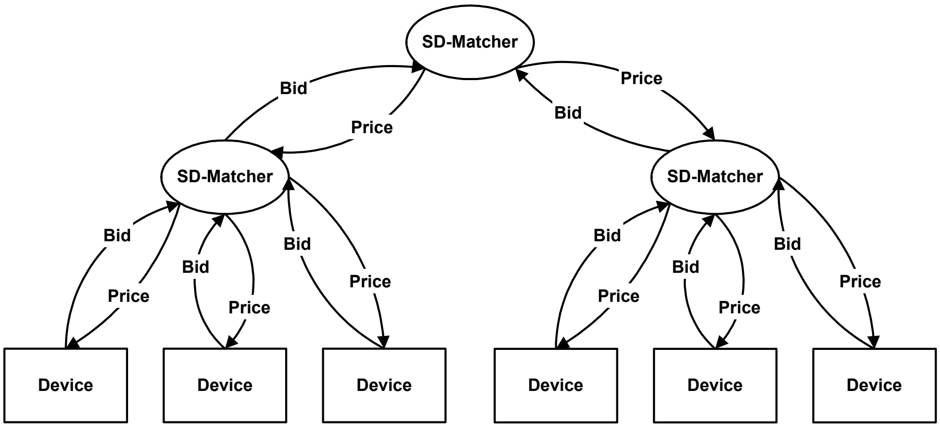


Figure 21: Hierarchy of supply & demand matchers in the PowerMatcher concept.

The SD-Matchers implement a distributed electronic market.

4.1.2.2 Device agent types and strategies

From the viewpoint of supply and demand matching, devices can be categorized by their type of controllability into the following classes:

- **Stochastic operation devices:** devices like solar and wind energy systems of which the power exchanged with the grid behaves stochastically. In general, the output power of these devices cannot be controlled. For its bidding function the device agent must rely on short-term power predictions. Furthermore, it must accept any market price.
- **Shiftable operation devices:** batch-type devices whose operation is shiftable within certain limits, like (domestic) washing and drying processes. Processes that need to run for a certain amount of time regardless of the exact moment, like swimming pool pumps, assimilation lights in greenhouses and ventilation systems in utility buildings. The total demand or supply is fixed over time.
- **External resource buffering devices:** devices that produce a resource, other than electricity, that is subject to some kind of buffering. Examples of these devices are heating or cooling processes, which

operation objective is to keep a certain temperature within two limits. Changing standard on/off-type control into price-driven control allows for shifting operation to economically attractive moments, while operating limits can still be obeyed (Figure 22). Devices in this category can both be electricity consumers (electrical heating, heat pump devices) and producers (combined generation of heat and power). Appliance of additional heat buffering devices can increase the operation flexibility of this type of devices substantially.

- **Electricity storage devices:** conventional batteries or advances technologies like flywheels and super-capacitors coupled to the grid by a bi-directional connection. Grid-coupled electricity storage is widely regarded as an enabling technology for increasing the penetration of distributed generation technologies at reasonable economic and environmental cost [b7]. Grid-coupled storage devices can only be economically viable if their operation is reactive to a time-variable electricity tariff, as is present in the PowerMatcher concept. The device agent must try to buy energy at low prices and sell it later at high prices.
- **Freely-controllable devices:** devices that are controllable within certain limits (e.g. a diesel generator). The agent bidding strategy is closely related to the marginal costs of the electricity production.
- **User-action devices:** devices whose operation is a direct result of a user action. Domestic examples are: audio, video, lighting and computers. From the agent point of view these devices are comparable to the stochastic operation devices: their operation is to a great extent unpredictable and the agent must accept any market price to let them operate.

In all described device categories, agent bidding strategies are aimed at carrying out the specific process of the device in an economically optimal way, but within the constraints given by the specific process. Note that this self-interested behavior of local agents causes electricity consumption to shift towards moments of low electricity prices and production towards moments of high prices. As a result of this, the emergence of supply and demand matching can be seen on the global system level.

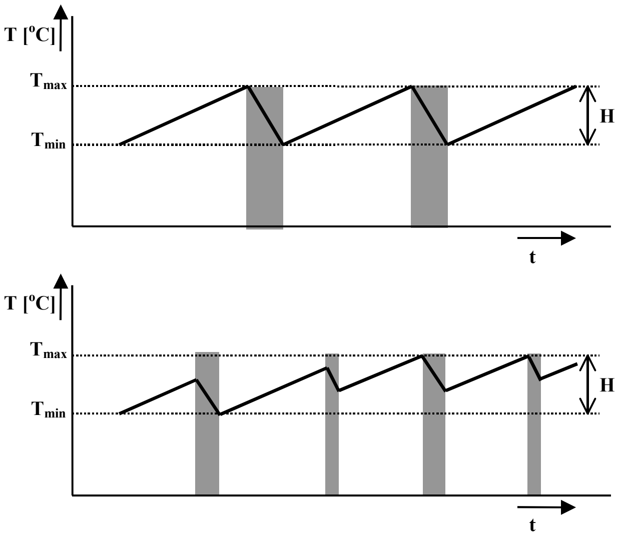


Figure 22: Operation shifting in a cooling process whilst obeying process state limits.

4.1.3 LV-cell Simulation Case

4.1.3.1 Case description

In a simulation study the impact of distributed supply and demand matching applied in a residential area was investigated. In the study, a cluster of 40 houses, all connected to the same segment of a low-voltage distribution network (an LV-cell) were simulated. Each house has a *Home Energy Management* (HEM) box, which implements the local energy management strategy of the house (Figure 23). The HEM-box incorporates the intermediate SD-Matcher functionality, together with energy performance feedback to the user, and the possibility for the user to set cost and task preferences. The latter makes it possible to set agent parameters of devices without a user interface.

Within the LV-cell an exchange agent implements the root SD-Matcher. The LV-cell is externally connected to a medium voltage network. Through this connection power can be obtained form and delivered to other parts of the distribution network. The electricity surplus of the cluster is delivered to an external electricity supplier, which delivers electricity to the cluster in case of local shortage. The external supplier can either be a full player on the local electronic market or set tariffs for delivery and retribution. In the latter case, the external tariffs are not influenced by the local price formation, and, typically, the retribution price will be lower than the delivery price. Then, the equilibrium price on the local electronic market will be bounded by the external tariffs.

Half of the 40 simulated dwellings are heated by heat pumps (electricity consumers), the other half by micro-CHP units (small-scale combined heat-power, producers of electricity and heat). The micro-CHPs are also used for production of hot tap water. Washing machines are operated as shiftable operation devices with a predefined operational time window; electricity storage is present in the form of batteries; stochastic operation devices are present in the form of photovoltaic (PV) solar cells and small-scale wind turbines; and user-action devices are represented as lights.

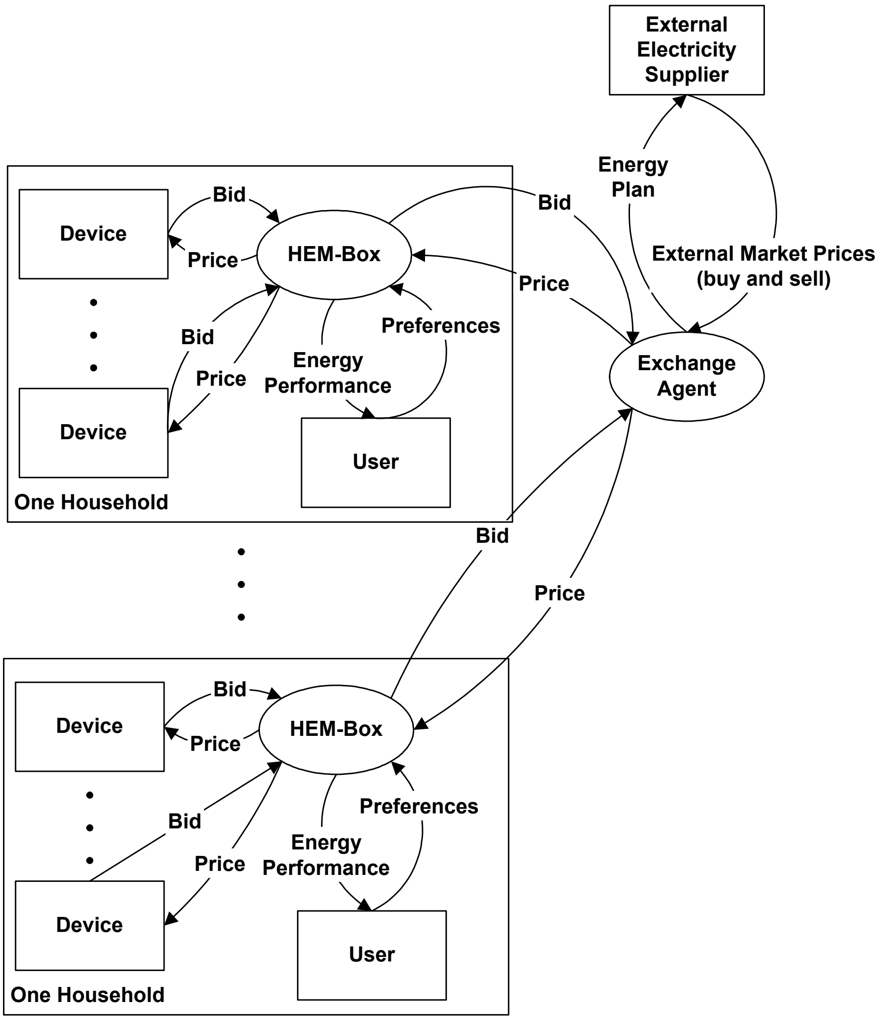


Figure 23: Set-up of the LV-cell simulation (see text).

4.1.3.2 Simulation result

Figure 24 and Figure 25 show the result of a typical simulation run for the LV-cell simulation case. In both plots the total consumption and the total production in the cluster have been summed into a single plotline, while production is regarded as negative consumption. The top plot shows the reference case in which all devices are free running. In this case all heating devices are on/off controlled, washing machines start their operation at the start of their operational time window, and batteries are excluded due to the absence of a real-time price signal according which they can be operated. In the bottom plot the SDM-controlled case is shown. Interesting features are:

- Around the 25th 15 minutes period there is a peak in electricity demand caused by the simultaneous starting of a number of heatpumps. Although there is also a small peak in local production at that moment, the greater part of the electricity needed to meet the peak demand is delivered from the external connection to the mid-voltage network. In the SDM-controlled case the peak in external feed-in is 30% lower, due to the reaction of different devices to the price peak on the electronic market at that moment. Consuming device agents shift part of their operation to other moments in time, producing agents shift as much as production as possible to this moment, and battery agents react by switching to discharging mode. In this particular case, consumption reduction accounts for 50% of the peak reduction, battery discharging accounts for 37%, and production increase causes another 13%. From the viewpoint of electricity distribution systems, this is an important result. The highest expected peak demand of a low-voltage net segment determines the capacity the coupling transformer and the network cables or lines. Reducing the peak demand lowers network investments in case of building new sub-networks, and defers network reinforcements in case of demand increase in existing nets.

- Introducing supply and demand matching results in a more flat and smooth profile of the electricity fed in from the mid-voltage network. Fluctuations in local consumption and local production are damped, and the mutual simultaneousness in the remaining fluctuations is high. The standard deviation of the feed-in from the MV-net in Figure 24 is 58% lower in the SDM-controlled case.

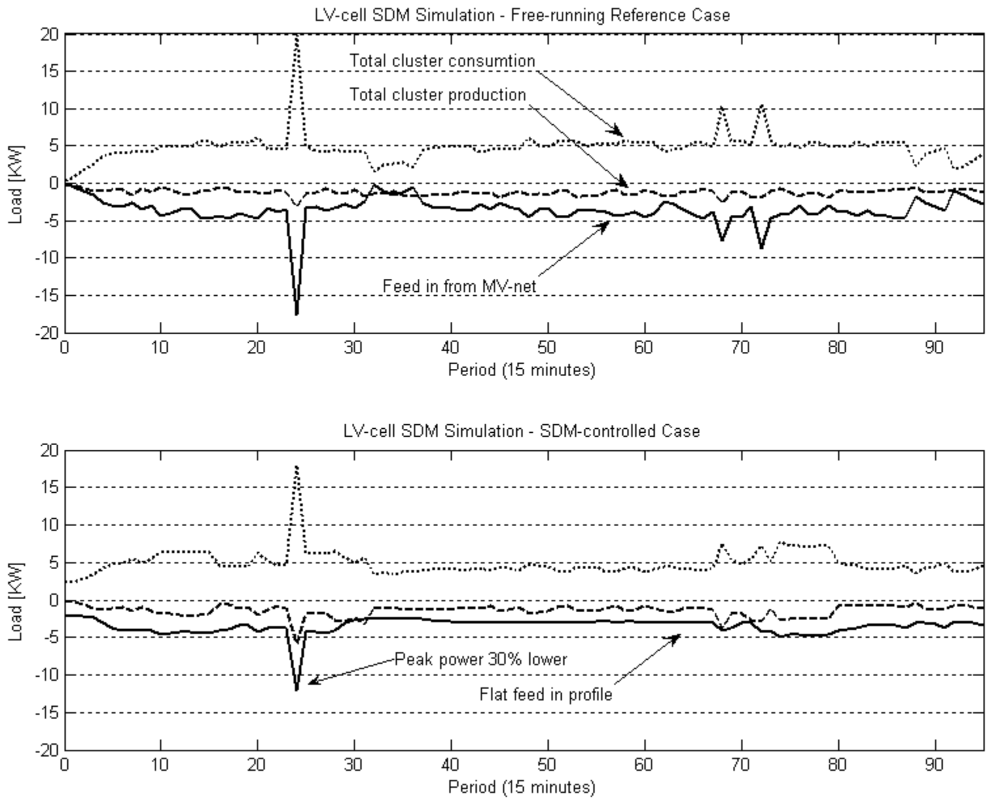


Figure 24: The result of a typical simulation run for the LV-cell simulation (see text).

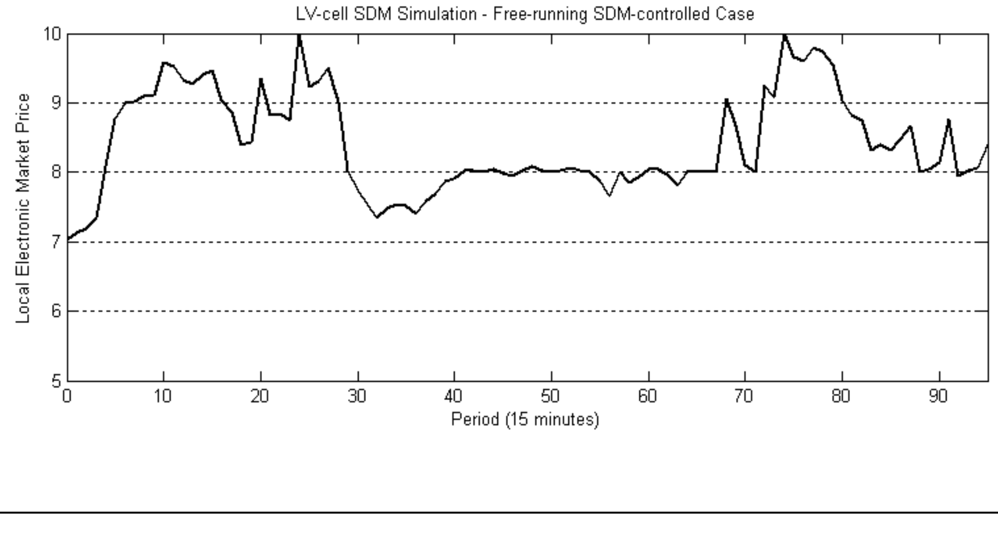


Figure 25: Price development on the electronic market.

4.1.4 Conclusion

Various drivers push the production of electrical power in the current electricity infrastructure towards decentralization. Multi-agent technology and electronic markets form an appropriate technology to solve the resulting coordination problem. The PowerMatcher concept proposed in this article is a market-based control concept for supply and demand matching (SDM) in electricity networks with a high share of distributed generation.

The presented simulation case shows that this concept is capable of utilizing flexibility in device operation via agent bids on an electronic power market. Via agent reactions on price fluctuations, the simultaneousness between production and consumption of electricity by devices in a sub-network is increased. As a result, the net import profile of the sub-network is smoothed and peak demand is reduced, which is desired from a distribution network operational viewpoint.

The real-time market proposed involves a closed loop of bids (up) and tariffs (down) during each time-slot (this time-slot being 15 minutes for instance). The bid includes the strategy as a curve of power exchanged versus the energy price: so the updated tariff sent gives directly the power to produce or to consume during the next time-slot by the bidder.

Using the tariff as the main global or local indicator is a powerful tool for the future network operator during critical situations: knowing the power-price strategies of the aggregated producers and consumers, a large disturbance in the system (for instance the loss of large power plants) could be managed by quantified local power responses (by tariff signal) in order to recover the global balance (nearly half an hour time response).

A limitation of this market approach (PowerMatcher) during normal condition is to require heavy ICT network (real time bids and tariffs) without defining large system coordination between the local loads and local DRs. The distribution of energy packets (injected or consumed) could be structured into the time in order to flatten the global energy flow through the EPS cell. The first benefit is for the DNO (reducing the constraints and losses to a minimum value), the second benefit should be for the end-customer (enabling distribution cost minimisation, tariffs incentives may come from the DNO) and the third benefit is for the environment (better energy efficiency for a same distributed energy volume). The principle of the PowerMatcher remains the same (the tariff as a main indicator), but an additional process (signals between agent and distributed ICT devices) is implemented to take benefit of local energy management system, forecasting tariffs in a wider time period (a day for instance).

This extension with multiple time bundles associated to based tariffs market remains difficult to clarify. The next chapter is about a similar approach with a consec market (defined by the ENS partners during the CRISP project).

4.2 Market mechanism at local scale: the CONSEC approach

4.2.1 Introduction

This chapter about CONSEC simulations presents a summary of the attached annexe document [A_D1.8] and also additional view of a possible structure of the market... The CONSEC is a tree-structured market mechanism for a set of consecutive time periods (CONSECutive).

The electronic markets principles have been introduced in [D1.7] for general purpose and specific EPS application purpose. This chapter shows how this market concept, including flexible real time electricity tariffs, is modelled and simulated. Finally it shows what are the expected performances in order to enhance the efficiency of the electricity markets, and how the distributed controlled energy play an effective real time balancing and stabilization role.

The market proposed in the previous chapter (PowerMatcher) consists in determining an equilibrium price, when the consumption and production are globally balanced, and then all trade takes place at this equilibrium price. On such a market a mechanism set electronically is needed to calculate the real time equilibrium price (short time scheduled energy) and their adaptation to real time events (power reserves used through a dedicated adjustment market). The exchanged information follows a process of bids from all the actors on the market.

Things becomes complicated with a *multi-commodity market*. Neglecting the dependencies between the traded commodities enables to treat *n* separate single-commodity markets. Another more complex approach consists in taking into account the possible dependencies during the bidding process.

The complete bidding process leads to a high difficulty: the computation is *NP*-hard, i.e. there is a conflict between the real time needed for the market and the EPS operation, and the time needed for the complete economical competition rounds with the checked adequate energy flows meeting the technical requirements (or optimisations).

The following definitions and concepts are used for the study and simulations:

- The *complementarities* or *synergies* are relative to the added value of the combination of the commodities. This is typical with multiple loads, controlled loads, production and controlled production that may managed in various tactics or strategies to deal with the expected real time prices.
- The *substitutability* is relative to the capacity of replacing a load consumption by another one, or a production unit by another one in order to take advantage of the price evolution. An example may be for a given time slot to replace a tap water heater by a washing process.

Since the winner determination problem of the general combinatorial auction is computationally hard, a number of simplifications and special cases are studied in the literature[5]. One natural case is tree-structured markets where any two bundles either are disjoint or one is a proper subset of the other, as shown in Figure 26.

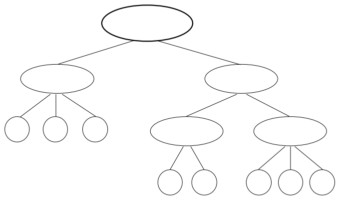


Figure 26: typical tree structure

From the CRISP cell approach, the market may be structured into (geographical) blocks of EPS area (for instance MV cells or LV cells presented in [D1.7]) and at the same time, into blocks of time slots. The power sequences of a given load is associated with a duration expectation that is included in a given time slot. Since a lot of kinds of loads and electrical characteristics exist, the proposed way is to keep as a binary decomposition of the time for the time slots from 15 minutes up to 8 hours, and to take into account 3 times 8 hours to recover the 24 hours of the day.

The figure 27 shows a simple illustration of geographical blocks (keeping in mind that the cells inclusion may be processed from the LV level up to the HV level). The Figure 28, shows a proposed day structure for local load distribution in a given cell. A complex key point for the agent of each cell comes from using local control for internal optimisation and also for external optimisation. In fact the decision comes from the local agent that assign different devices to these two different goals.

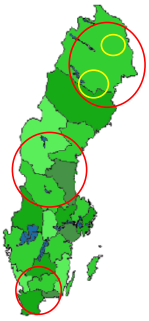


Figure 27: Simple example of geographical blocks

On a Consec market the bundles of the commodities are defined, expressing substitutability and complementarities needed. The Details of the mechanism are provided in Carlsson and Andersson: *A Flexible Model for Tree-Structured Multi-Commodity Markets* [5].

As said previously the mechanism is built on predefined bundling of commodities (e.g. consecutive time periods). In Figure 28 we see an example of such a bundling. The bundling is arbitrarily defined by market needs, as long as it is tree structured – that is, two bundles are either disjoint or one is a proper subset of the other.

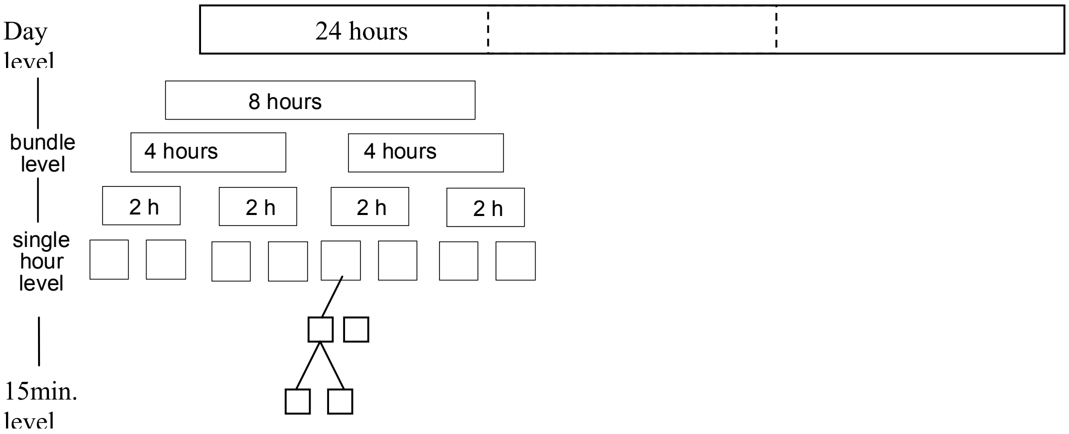


Figure 28: A time-slots table from 15 minute up to 24 hours

This approach meets the well known time slots used in the large interconnected EPS market today: the scheduled production and consumption from each day for the following day, with a main time slot of one hour. Then the time step is reduced by the TSO into half an hour or 15 minutes times slots. Compared with this existing classes, the additional time-slots of 2 hours, 4 hours and 8 hours enable the agent to classify differently its portfolio of partially controlled loads.

Depending on the minimum duration of a process launched (power consumed or produced) and the maximum period required for this process, it is more or less attractive for the area power control purpose: the flexibility capacity is increased both with a low rate of duration / period and with a short involved duration. The agent needs these two time parameters (duration of the process, period between two processes) for making the rigth tariff choice (launching the process at the rigth time) including the right level of technical constraints (avoid local bottlenecks). For loads and production contributing to this market, two kinds of bids are considered:

- the agent takes advantage of the existing mid-term external price. A specific signal may be sent by the agent to start the local loads involved in at the rigth time (> complementarities).
- flexible bid: the decisions are taken in the short term for near real time execution, for taking advantage of the last minute changes in the tariff signal. By fault, in case of normal flatten prices the mid-term strategy is followed and the power exchanges are distributed among the various times-slots (as for the block bid) (> substitutability).

A large part of the local production and the local consumption is not controlled: the consec market takes advantage of the scheduled and updated tariffs along the day, taking into account specific conditions expressed by the bidders (for their own load or production strategy) and also specific technical limitations (internal information into the cells and information exchanged between the cells).

In the ideal way, the agent has the local data of the energy exchanges (initially scheduled data, real time data and also data scheduled for the following several hours). The global gain (profit from tariffs difference in time slots, the agent deals with the energy exchanged between the cell and the external part of the cell) is preferred to the local gain while technical constraints remains acceptable.

As viewed in the PowerMatcher approach, the bid may be expressed by the agents with enriched curves given the exchange of power for a given energy price, as illustrated in the figure 29. The resulting tariff from the market is then followed by each agent of each cell to launch or not the processes ready to run. Hence new processes are launched and old processes have finished, the agents have to check their own bid capacity (power controlled reserves) for the following hours.

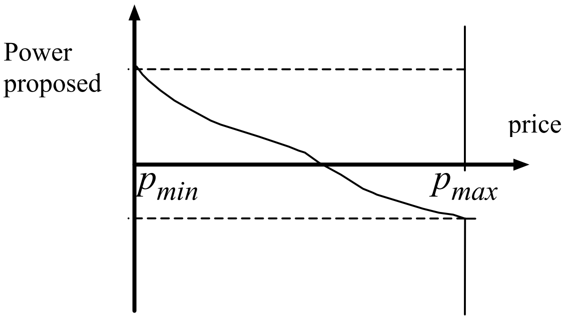


Figure 29: Expressed bid between prices Pmin and Pmax

The scalability is a problem with the future possible multiplication of the bidders. The Consec market may handle an advanced solution of the CoTree algorithm (proposed by Andersson and Ygge for a single commodity markets [2])., making possible to express the dependencies between time slots that are traded simultaneously.

The idea presented in the Figure 30 is to keep a clear paralleled approach for the grid topology and an associated market topology, enabling to check step by step the coherency of the local bids in terms of technical limitations. In the figure a single node in the market tree is symbolised by a circle, and a complete sub-tree that is not drawn in detail is symbolised by a triangle.

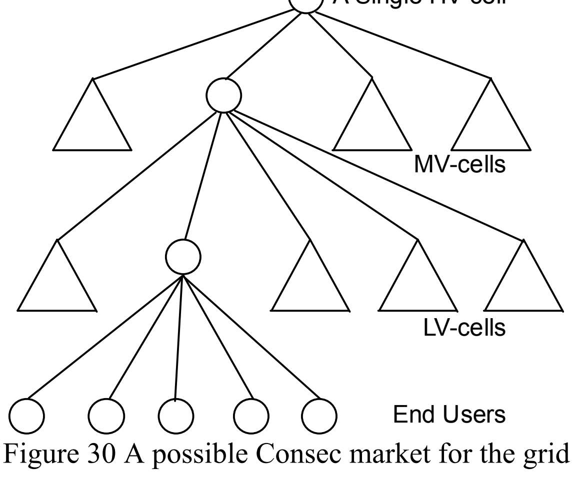


Figure 30 A possible Consec market for the grid

4.2.2 Simulations of a Day-Ahead Market within an LV-cell

The simulation investigates the impact of distributed supply – demand matching in a residential area with all houses connected to the same LV-cell. The case presented in chapter 4.1.4 is taken again.

Two different approaches are simulated. One where a matching is performed on a 15 minutes resolution using a Newton-Raphson optimisation routine at local level. The other with the Consec mechanism.

4.2.2.1 Simulation Set -Up

The LV-cell is composed of 40 households, as illustrated in Figure 31. Some of them have generating units: 25 houses are equipped with micro-CHP units. The energy strategy deals with thermal and electric constraints. The smallest time-slot taken into account is one hour.

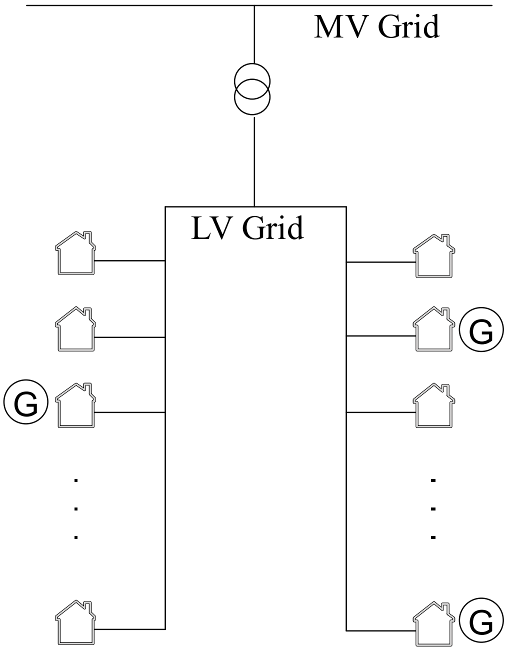


Figure 31: The LV-cell scenario based on 40 household actors

The simulations are about a week during winter or during summer. Outdoor temperature data are from a cold winter week. Power consumption, capacity limits, etc. of individual houses are based on typical Swedish data on houses built in the 1960-70s. The local market is assumed to be self sustained every single hour. The external market is used as a buffer for the balance. In these simulations we have strived towards a long run balance between local supply and local demand, but in reality we find it the most plausible that most LV-cells in a foreseeable future will stay net consumers.

To strive for the local market to be in balance in every moment is another possible goal. This is hardly justifiable in practice, as it is not efficient during normal running condition. But during intentional islanding due to emergency conditions, this approach may solve the market aspect in such a situation (special emergency tariff adapted to the local production costs).

On top of the building heating system all actors with traditional heating are assumed to have an electrical tap water heater, and we split the consumption of these over eight hour blocks, with less demand during night compared to day time. Finally the households were assumed to run some washing processes or similar with different demands on starting time and finishing time.

As shown in figure 32, the simulations assume that the local price may vary between a minimal value (selling the electricity to the external market) and a maximal value (buying the electricity to the external market). This assumption is not true today with policy incentives for enabling DG and renewable energy insertion, making the production price attractive. The external price limitations may be fixed or variable as indicated in figure 32 and figure 33. These figures are illustrative, the price indicated on figure 33 are rather relative to a massive pool (large volumes of energy exchanged), and the price indicated on figure 32 is rather relative to local energy prices at LV.

A question behind this approach is how to transmit these daily prices high variations at the transmission level to the distribution level in order to create positive feed-back on the local demand and production daily power curves. The SDM may enable to shave the daily peaks by a better load and production local distribution.

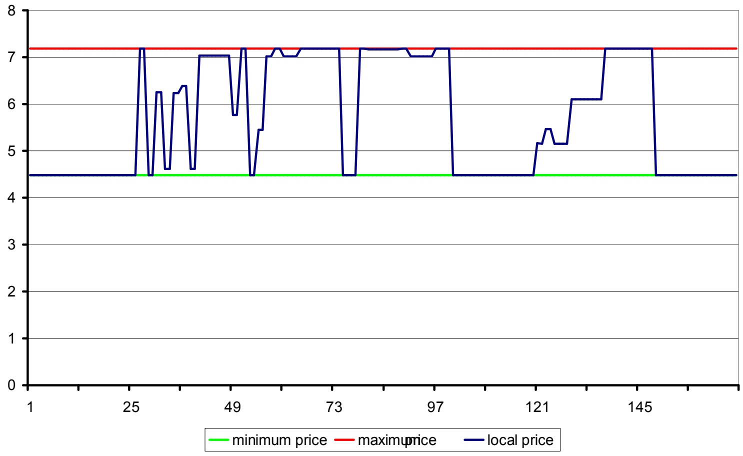


Figure 32: variable price limited by minimum and maximum (cent-euro/kWh versus hour)

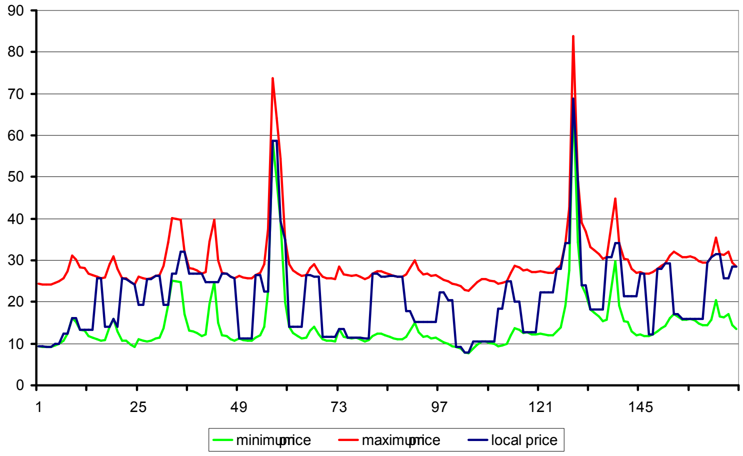


Figure 33: Local market with dynamic external market prices (euro/MWh versus hour)

Tap water heaters, dish washer and washing machines are modelled rather straightforward utilising the possibility to enter substitute bids on a Consec market. These actors are examples of a class of actors that we have denoted freely *controllable devices* due to their characteristics.

Given needed information, the software agent representing a flexible load decides on what block(s) to enter an adaptive bid on. One possibility is to choose the largest defined block of consecutive hours that fits between earliest starting time and demanded ending time.

On the other extreme we have the *micro-CHP* units that are modelled such that they want to run for a number of hours on a row when started. This is expressed entering most of their demand[1] as a bid on the same resource over a block of consecutive hours. The houses with micro-CHP units are assumed to have some extra heat buffering capacity (a hot water accumulator). The power produced may be tuned.

The heating systems provide us with a flexible capacity for the demand, depending on the thermal inertia and the comfort tolerance required. A similar load characteristic exist with the cooling systems that have cyclic running duration. These cases involves thermal constraints (temperatures to meet) and electrical constraints (temporal

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[1] Supply is modelled as negative demand.

distribution of the running periods between the local controllers). A large thermal inertia enables in general a high electric flexibility for the expected control (by dedicated signals or by tariff signals).

4.2.2.2 Results

The first result presented is obtained with the static external prices. The, Figure 34 shows that the price has no wide stable period, it is often at the minimum or maximum value, depending on the local unbalance situation (minimum price if the cell injects power in the external system and maximum price if the cell absorbs power in the external system).

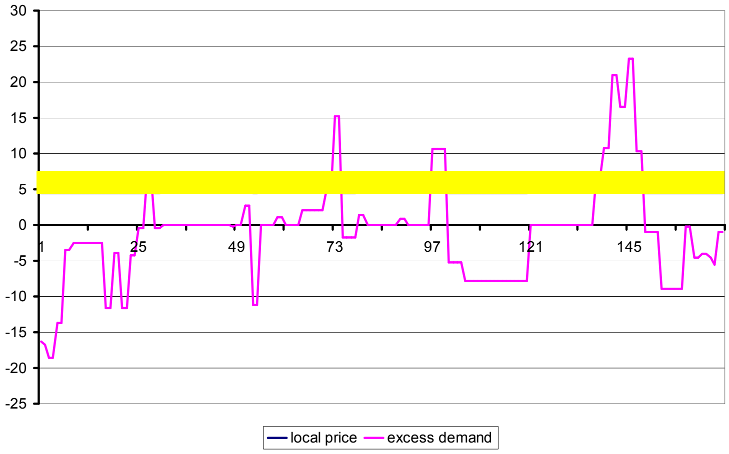

Figure 34: Excess demand and market prices of the LV-cell market

Moving our focus to Figure 35 we can see the relation between total demand on the local market and its excess demand, i.e. what is left for the external market to meet when the local match has been performed.

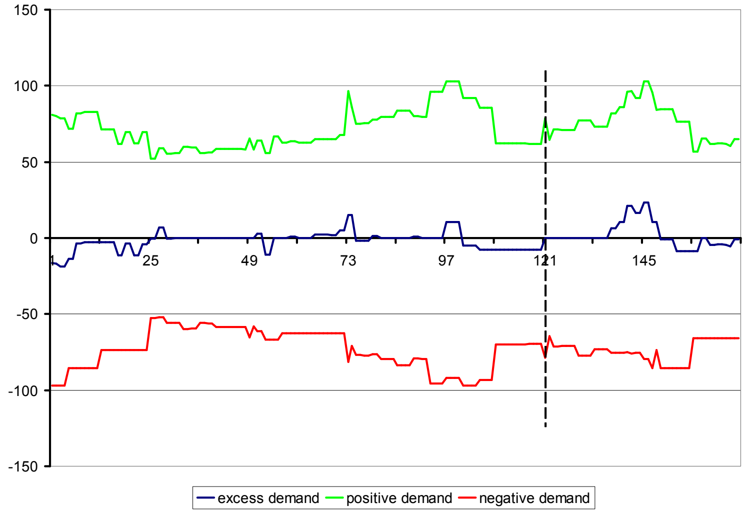

Figure 35: Demand profile of the simulation with static external market prices.

On figure 35, the vertical broken line highlights the smooth match between supply (negative demand) and demand on the local market. When local supply and demand are not matched the higher voltage grid and external market acts as a buffer. From a system viewpoint we could loosely define the objective of a local market with fixed external prices to be minimisation of the flow over the substation that defines the border between the local market area and the rest of the world.

As we see in Figure 35, even though the local market is almost in balance over the full week (with a total excess demand of -154 kWh) we do not reach local balance for each hour. Whether this should be the ultimate goal or not could be discussed, but we argue that it is not efficient to try to reach balance neither within such small markets nor within such small time horizons, if it is an interesting goal at all.

The building heating process is shown for a cold winter week on Figure 36. In the figure we see both outdoor temperature and the allocations, hour by hour to an electrically heated house.

The bids of the heating system are divided into two parts; a base part expressed in single hour bids, and a flexible part expressed in adaptive consumption bids over blocks of two consecutive hours and of four consecutive hours.

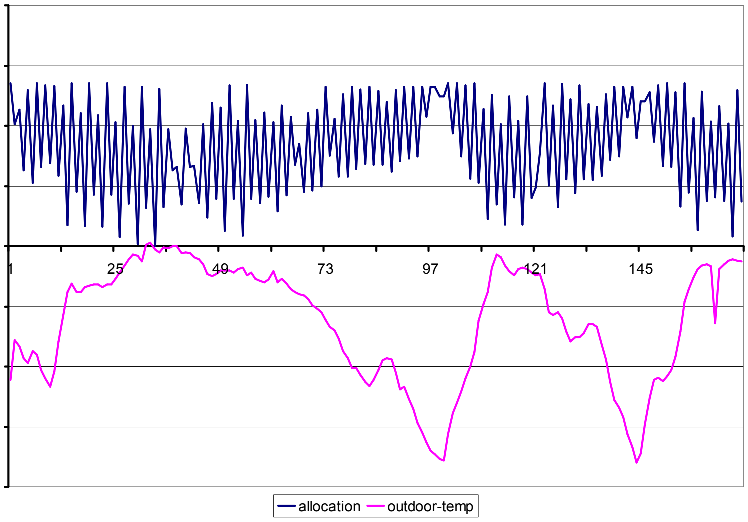

Figure 36: traditional heating system versus outdoor conditions

The fluctuations are related to two factors. First and most essential we have the aim of the heating system to fulfil its duties at the lowest cost as possible, second we have the allocation routine of the market mechanism, giving allocation information on flexible bid resources. Currently, the allocation routine does not try to even the allocation to an individual actor between hours with equal price (the same lowest or highest price for more than one hour of a block). We can see a clear difference if we look at the average allocation to the heating systems of all houses with traditional electrical heating, on Figure 37.

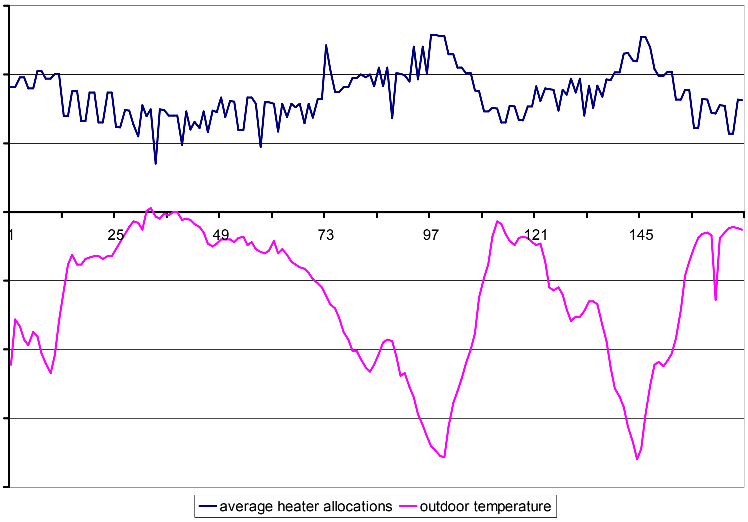

Figure 37: average allocations to the heating systems

Entering an adaptive buy or sell bid on a block of hours means the bidder is able to take the resource anytime during the duration of the block. The building heating system has a comfort tolerance to utilise to move consumption between hours, illustrated in Figure 38.

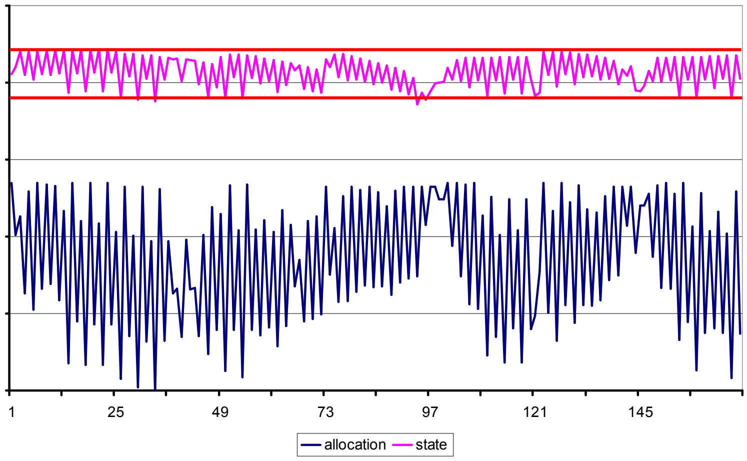

Figure 38: Allocations and state of one of the houses with electrical heating system

The outcome for one of the micro-CHP units is illustrated in Figure 39. The heating system of the house is assumed to have larger tolerance than the system shown above, due to a hot water buffer. We find it rather plausible that a household installing a micro-CHP unit for heating of the building (and tap water) would consider combining it with a heat buffer to increase flexibility and allow longer running time when the unit is started.

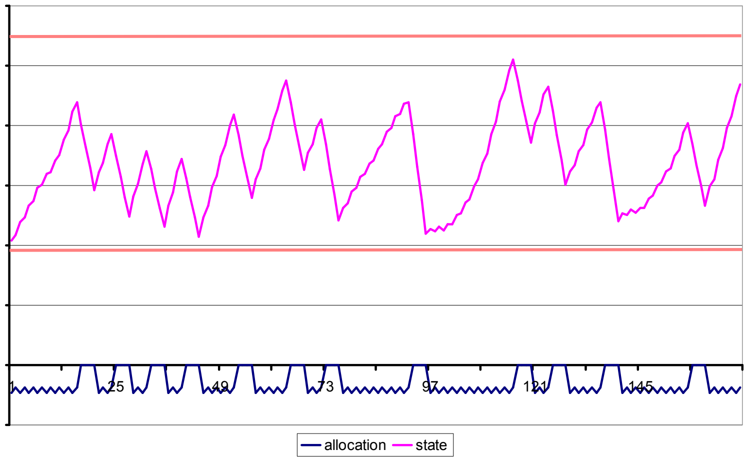

Figure 39: Allocations and state of a residential building with a micro-CHP unit

The micro-CHP unit of figure 39 is used for building heating and a heat buffer. As shown the system is able to hold temperature within its borders (the red lines in the figure).

In Figure 40 we see that there is no direct connection between when the unit is running and market prices (and that the difference in allocation between minimum price and maximum price is small due to the bidding behaviour of the actor).

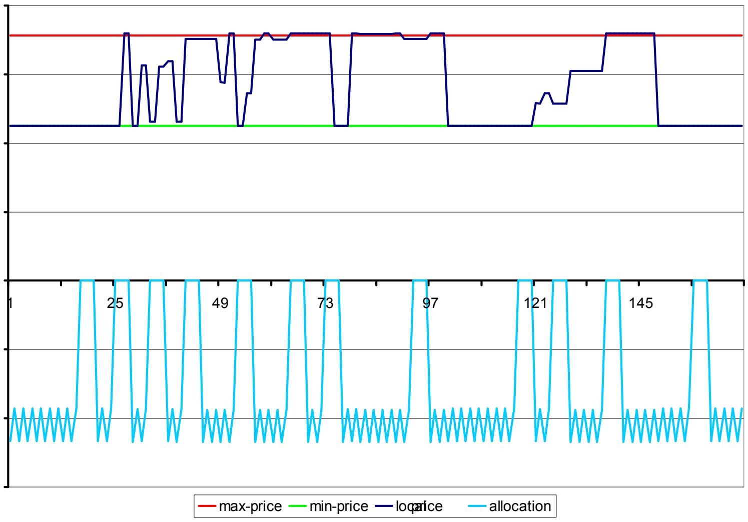

Figure 40: Local market prices and the allocations to our example CHP unit.

The allocation is based on two components; most of it is related to a block bid on the same resource during a four hour block. The last, jagged part of the allocation stems from part of the (negative) demand expressed in flexible bids. The comment on the jagged shape of the allocation curve given above for the other example actor holds for this one too.

Similar simulations have been carried out for the case of variable external prices. The results are quite the same for the local controlled devices (loads and generating units), involving a main position at the lowest price or at the highest price. The difference is when a high peak price appears, the consec mechanism leads the local agent to allocate the controllable production and consumption of the cell to an equivalent producer. This stabilisation effect at large scaled and logical feed-back is illustrated in the figure 41.

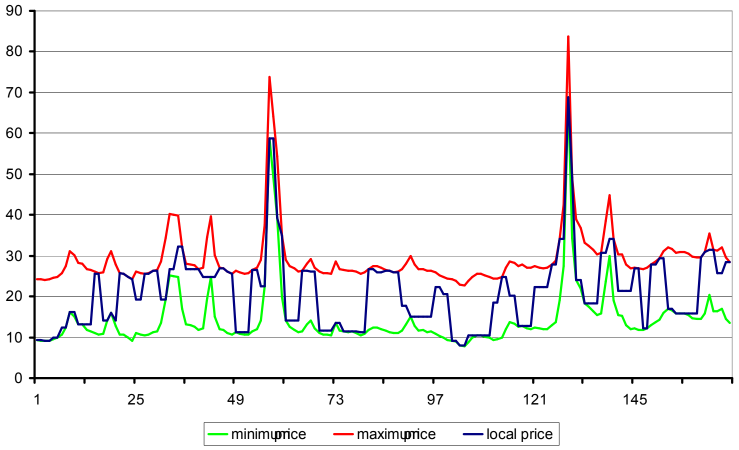

Figure 41: local market price between variable minimum and maximum prices

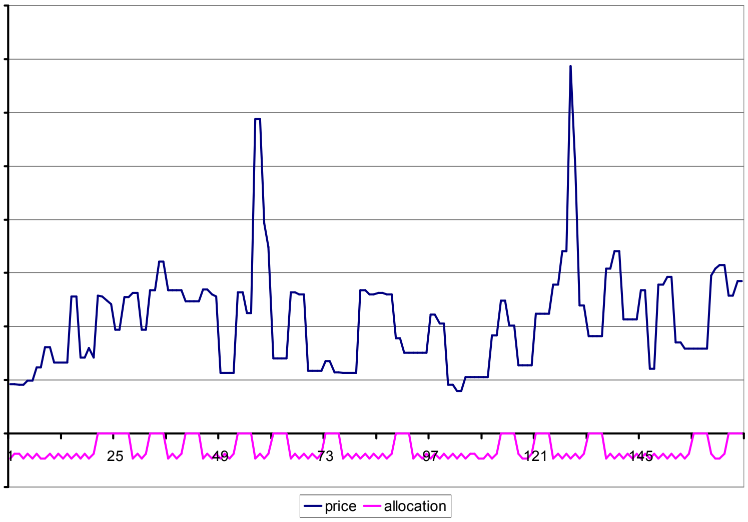

Figure 42: Prices on the local market and allocations to a micro-CHP unit.

The figure 42 shows the power allocation of the CHP: the DG injects power in the cell during the pric peak as expected.

4.2.2.3 Analysis

The *bottlenecks in the grid* (power line capacity limitations or substation capacity limitations) feeding the cell may be limited thanks to tariff signals, indicating the expected difficulty during the next hours. The external price of the cell may be changed along hours, keeping tha adequate average value of the market in the mid-term. The market gives the real average price, and the local agent (may be the DNO) changes some hourly parameters in order to meet the local technical constraints and to allow a better distribution of the power during the mid-term. This tariff incitation may be used for local problems (voltage or current limitationos) or also to make contribute local controlled devices to an external need (global difficulty maintaining SDM).

With dynamic external prices the response to global disturbance is natural: in case of excessive price (low or high), the controlled devices in the cell react in the right direction for the global market. A problem is the tool for the local DNO to maintain normal local electric condition if the response becomes excessive. A solution is to have a possible adjustement of the price by the local agent, making the variable price dependant on the real time situation into the cell. If no problem in the cell, 100% of the variable price is applied at local scale, if technical limitation occurs, only a X% of the variable price is applied (X being updated regularly to the state inside the cell).

Making the distribution actors involved in the real variable daily price should reduce the daily power peaks at the global scale.

The principle of net local power balance at the scale of the cell is not really interesting and not so connected to the principle of market. The real interest is to have predictable power flow for a day-ahead and also sufficient local power reserves (controlled devices) in order to contribute enough to the global stability needed. If an effort is done at each level of the cells in order to avoid energy peak and large fast power variation, the EPS network structure may be used more efficiently.

4.2.3 Wind Farm and Local Consumer Market Scenario, Öland

The Swedish island Öland is an extremely natural market node. It is connected to the mainland grid with a single power line at Linsänkan, called LIN in Figure 43.

The total number of customers is 24,000.This market is composed of customers and producers (wind-power mainly) connected to the MV long feeders (50kV). The classification into market cells depending on the voltage level has been applied to this case. This principle may be generalized to any part of the large interconnected network. A direct interest is to keep information about real configuration of the network (in case of flexible distribution) and to prevent technical constraints during the bidding bottom-up process.

The existing local markets with different scales enable specific future running conditions, for instance during critical states of the network or also in case of intentional islanding.

Another point is the possible introduction of the grid cost for the transmission or the distribution of the local energy. A specific and flexible grid tariff allows the operators to deal with future limitations in the lines during some time slots, assuming the optimisation of the network with the scheduled production and consumption. This approach is complex caused by the involved strategy of the DNO for deferring or not investment in network reinforcement.

New offshore wind-power plants will be connected to the 50 kV grid of Northern Öland. Studies performed by Sydkraft within the project [16] show that an increase of the installed capacity in the order of 20 – 30 MW could be handled without large network investments if an efficient and local energy management system is developed.. A solution investigated is creating *a local electronic power market.*. The objective for the local DNO is to meet the capacity limits in the grid along the year with the same network structure. The wind-base production is assumed to be partially controlled, and a part of the local consumption is assumed to be controlled too.

4.2.3.1 Simulation Setup

The capacity limit on the lines of the island is nearly 30 MW. The offshore projects was not scheduled when the 50kV grid have been installed. One 10MW project and another project around 35MW exist, leading to difficulties for nominal power injection during low consumption period in the north area. As the wind production is highly variable, the simulations assume a possible time control of the energy exchanged along the 50kV lines, using the local assumed capacity of generation control and loads control.

Öland residential consumption is quite continuous along the year due to tourism effect: the electric peaks are nearly 5MW around Borgholm. The simulation scenario is based on the volume of planned wind production and consumption control capacity located in Borgholm. In Figure 43 we can see the localisation of the planned wind farms, the simulated local market, and the grid capacity bottleneck

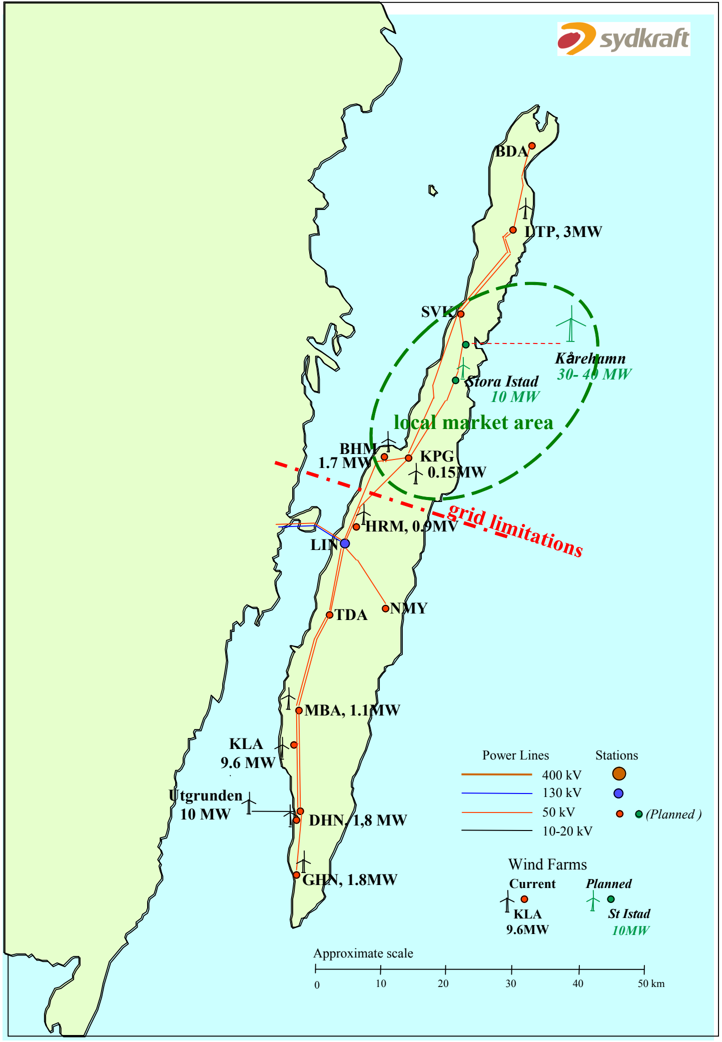

Figure 43: The Öland 50 kV grid with planned wind

A hourly resolution is defined for the market, and fixed prices are used as long as the grid normal running condition are met. A minimum price of 2/3 of the external price is taken, and a maximal price for the local market equivalent to the external price.

Time series on the production of a number of Swedish wind turbines and wind farms have been collected during the last decade [1]. The data has an hourly resolution. As no information is available from the planned wind farms we have used data from a 45 MW offshore wind farm situated between Öland and Gotland.

.Figure 44 and Figure 45 represent a summer month and a winter month respectively: The 30MW threshold is indicated in the figures. The main production is observed during the winter. The interesting thermal buffer provided by heating system is investigated for the load control purpose during this period of year. The summer time is less problematic for the grid capacity as indicated in Figure 44.

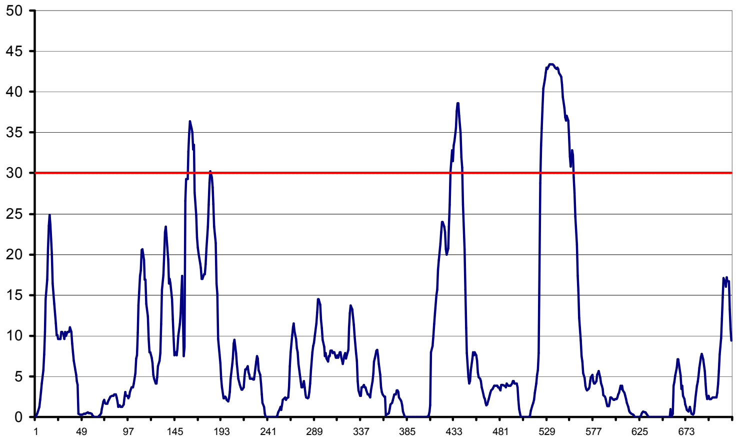

Figure 44: a month of pwind production, June 2001, MW versus hour.

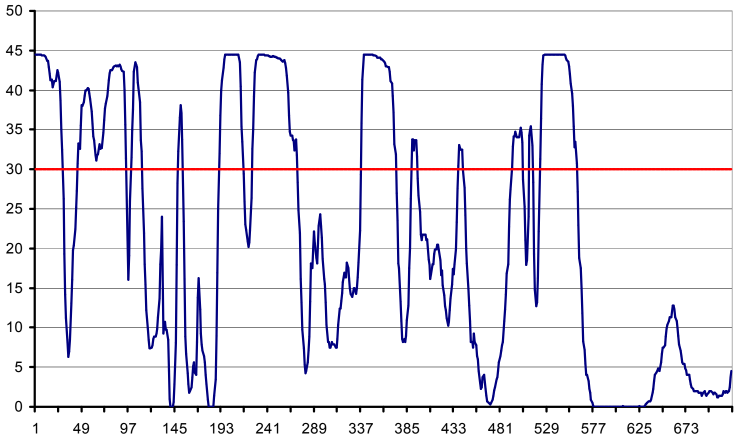

Figure 45: a month of wind production, November 2001, MW versus hour.

The simulations have been performed in steps, starting with only households, adding the district heating system, and finally adding the industrial load.

Three industrial sites have been modelled (two existing sites and a virtual one). This actor has been modelled with a simple "as soon as prices fall, my demand increases"-strategy. As this is a non-existing, could-be-there actor, the size of the actor(s) could be anything from negligible to dominating, we choose to make it a 7 MW max capacity load (based on the existence of an old 5 MW industrial boiler load that is not in use any more).

Among the residential customers around 800 have an electricity consumption that indicates the use of electrical building heating. As in the LV-cell scenario we focus a few processes among these consumers that have a significant built in flexibility; building heating, tap water heating, and washing processes. The 800 actors have not been simulated as individual loads but on an aggregate level.

The time series data [1] are the input to the bidding of the wind power producer. The properties of wind based production give that the bidder enters single interval bids only. He has no need for the Consec capability to express synergy or substitutability.

In this simulation scenario we used building heating and tap water heating processes. Building heating is outdoor temperature dependent, as well as it depends on user preferences. Tap water heating mainly depends on user preferences and buffer capacity. Tap water buffer capacity in a normal Swedish home is large (a day without power is not a problem)

Building heating system: In the simulations we have used input data regarding a cold winter week. We defined a base load for a zero degree outdoor temperature and estimated that a one degree change in outdoor temperature will give raise to a +/-5% adjustment of demand. User preferences where defined with a constant demand for the same indoor temperature and with a constant accepted deviation from this temperature. The accepted deviation from ideal indoor temperature was utilised by the bidding agent *(i)* to express part of the demand for electricity in flexible bids (on a two hour and a four hour scale), and *(ii)* to be able to construct bids that are decreasing in price. The ability to express parts of the demand in terms of flexible bids was calculated as a linear optimisation problem using a standard simplex routine.

Tap water heaters: Tap water heaters have a rather large flexibility, and we assumed that their demand could be expressed entirely using flexible bidding strategies, entering bids mainly on blocks of eight consecutive hours.
Currently the installed capacity of the **district heating system** is around 10 MW, mainly fuelled with bio mass, only a minor part is electrical. The simulations assume that electrical boilers consume excess power from the wind farms.

The **district heating system** has been modelled with an outdoor temperature dependency similar to the one of building heating systems. The system serves a bit more than 400 buildings, on average with a substantially larger demand than the residential buildings of previous section. It has a maximum capacity of approximately 10 MW, and we have estimated its demand to be a bit higher than the aggregate demand of the individually heated houses. The system as such has a large buffering capacity and moreover, it has a 100 m^3 tank buffer. This buffering capacity has not been modelled in the simulation. That is, in an extended study we could assume that the capacity of the district heating system to meet excess supply of the wind farms is higher than what we express here.

Essential is that the district heating system is a hybrid system with alternative fuel. That is, it has a negligible demand for electricity when the prices are high, and when the price is lower it moves (parts of) its demand to this market. The *bidding strategy* of the district heating system is based on the definition of some *threshold price.* That is, a price where it becomes profitable to switch to (from) electrical heating, Figure 46 (right). Depending on switching costs, the system enters bids on single hours or on blocks of consecutive hours. When we take buffering capacity into account, parts of the demand is expressed in flexible bids.

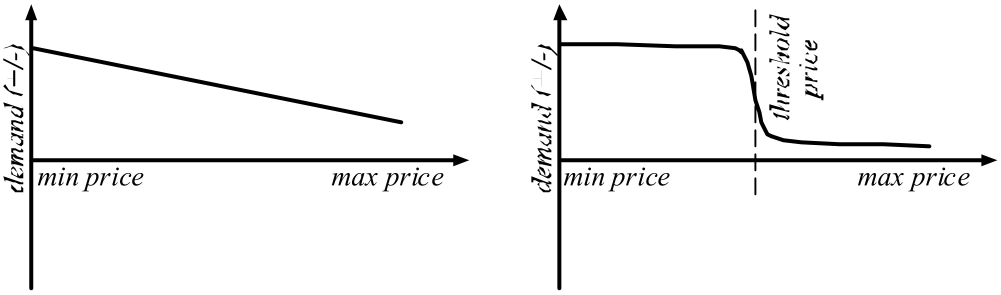

Figure 46: Two possible bidding strategies.

There are enumerable possibilities when it comes to bidding strategies. The results given in this report are based on a couple of simple and straightforward bid shapes (as in Figure 46) and utilisation of the possibility to enter block bids and flexible bids expressing synergies and substitutability.

4.2.3.2 Results

Residential building heating, tap water heating, and washing processes are first analysed. Only the wind power exceeding 30MW is represented in the figure 47 (first week of November on figure 47). The residential building heating and tap water heating loads in Borgholm (800 houses) cannot balance the wind extra power. The buffering capacity plays a main role: the 25 first hours show a continuous windy condition.

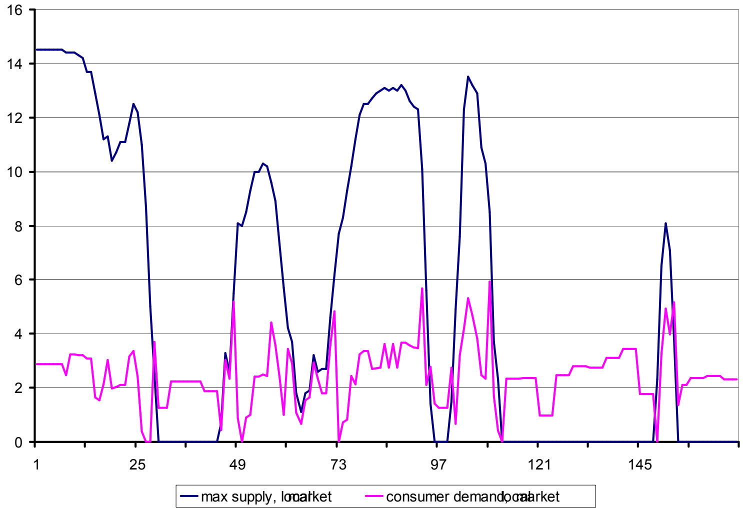

Figure 47: residential response to wind extra power, MW versus hour.

The price on the market associated to this windy week is shown on Figure 48 (3 means external cell price).

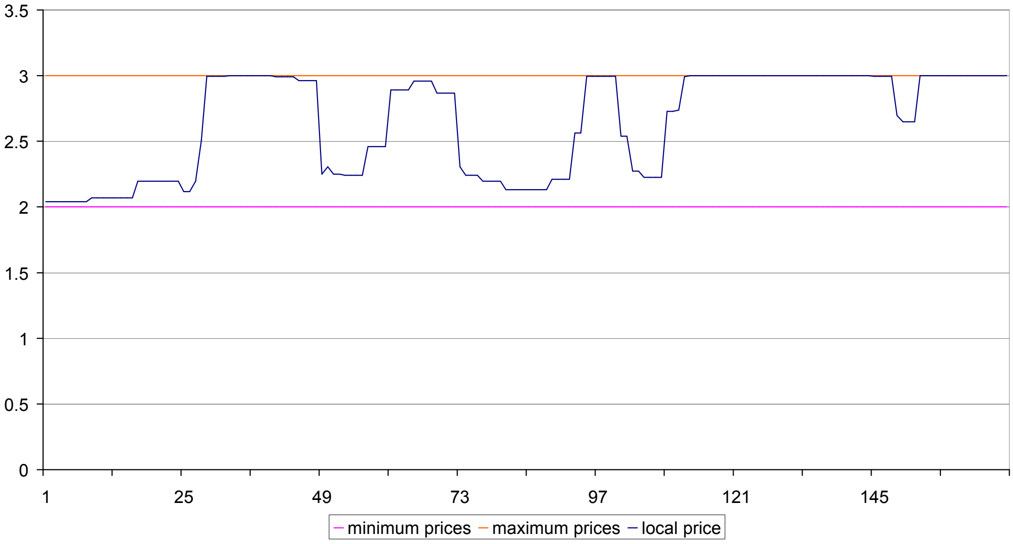

Figure 48: Prices resulting from the unique response of the residential consumers

The district heating system is added to the residential control for the adjustment of wind extra power. The figure 49 shows that the extra power is better balanced by the local controlled demand.

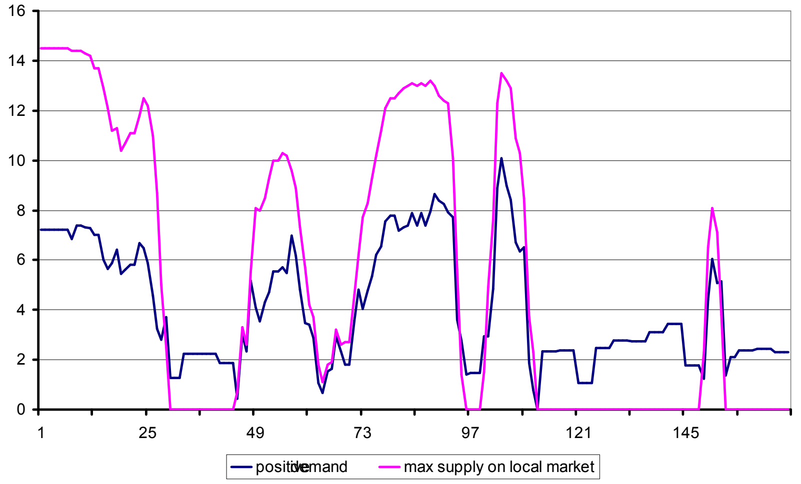

Figure 49: residential and district heating system response, MW versus hour.

The minimal price on the market is increased due to the bid strategy of the district heating system, as shown in figure 50. The threshold for using extra wind power is between 2.5pu and 3pu for this actor (changing from a primary energy to the electricity one).

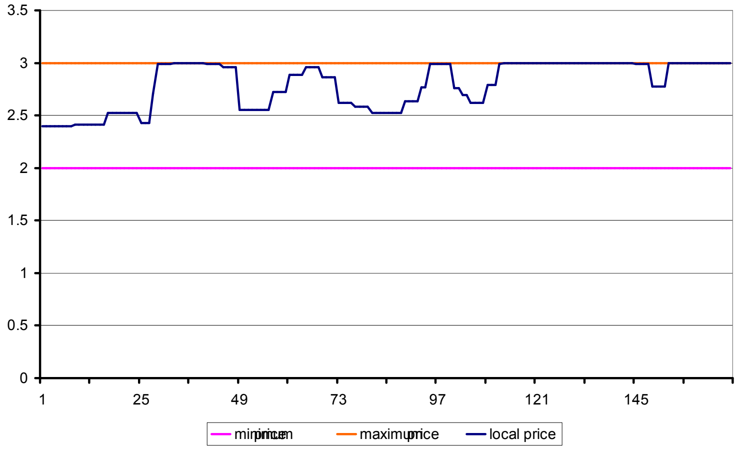

Figure 50: Prices resulting from the response of the residential and the local district heating system.

When adding the industrial controlled demand to the two previous kinds of loads, the extra wind power is still higher than the total and local control load. The industrial sites are assumed to provide a controlled capacity of nearly 7 MW. All the controlled load capacity is used, as indicated in figure 51.

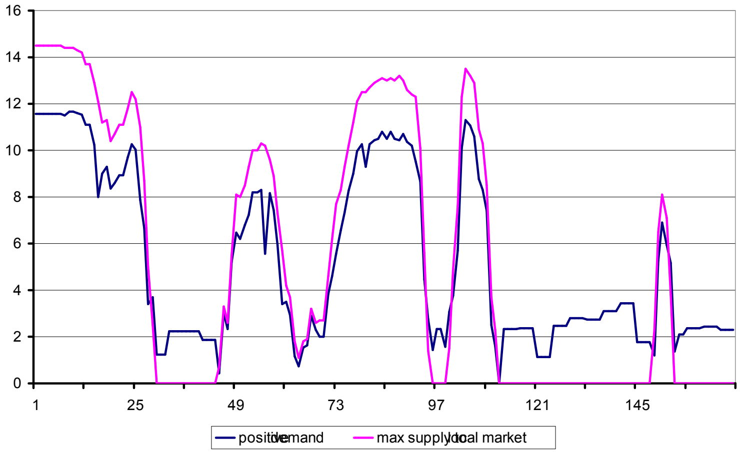

Figure 51: all the controlled local load response, MW versus hour.

As demand increases, prices on the local market increase too, and the average price when there is a local supply is 2.84, as indicated on Figure 52. This approach is quite simplified since the energy volume contracted by the district heating system and by the industrial customers should entail lower prices for them compared with the residential customers. Assuming that the residential customers are aggregated in virtual large control loads, the placement of them in a same market place remains realistic.

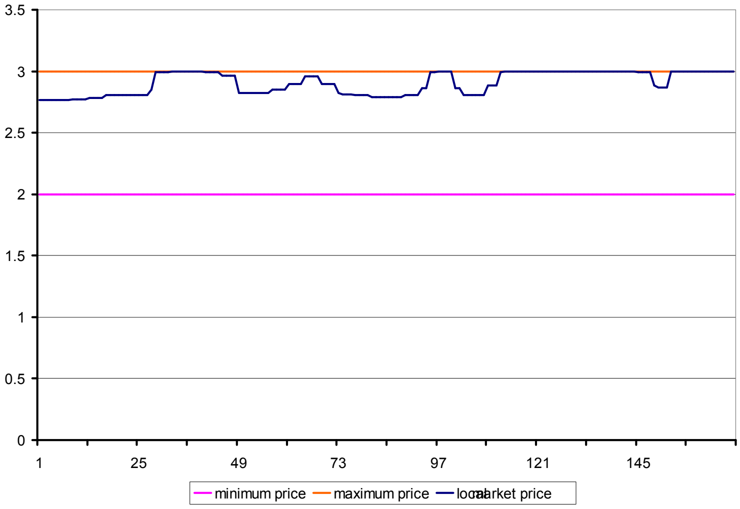

Figure 52: Prices resulting from all the local load controlled systems

This final result in price has consequences on the power allocation of the district heating system (DHS) as indicated in figure 53 and in figure 54. When price fall down 2.5pu, the DHS allocates all the power produced from electricity source, see on figure 53. When the local price is stable around 2.84pu only 40% of the power is from electricity source, see on figure 54.

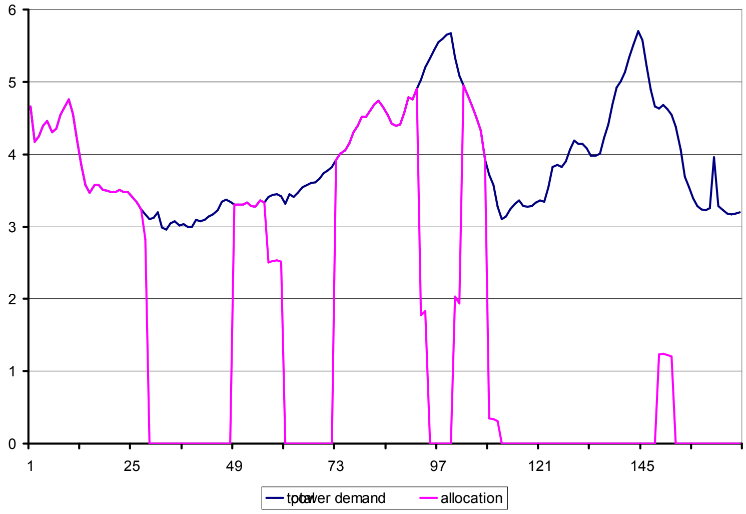

Figure 53: district heating demand, electric allocation relative to local price, all loads

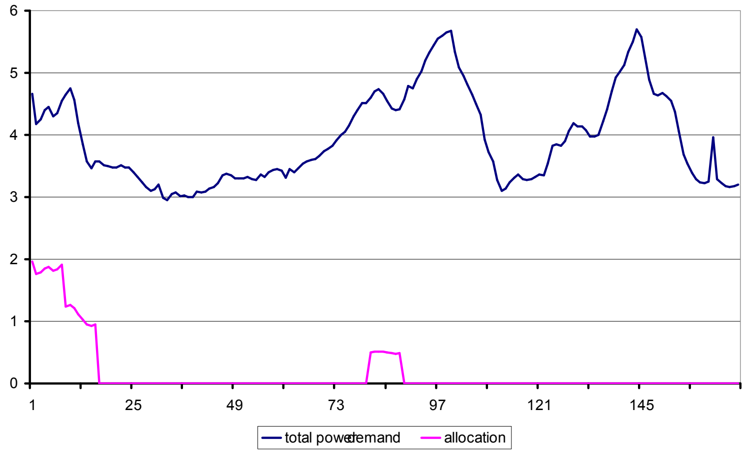

Figure 54: District heating demand, electric allocation relative to local price, no industrial load.

If the capacity limit would have been closer to the max production of the wind farms, the situation would have been different of course. Not only would the excess supply be less, but many of the problematic periods would last less, as indicated on Figure 55.

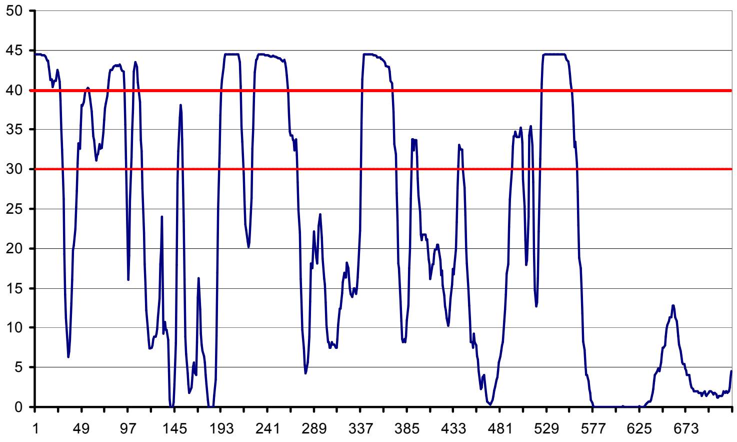

Figure 55: The impact of a 30 MW grid capacity limit and a 40 MW limit.

4.2.3.3 Analysis

Without grid limitation problem due to periodic extra local generation, the local market as described here is difficult to justify: since the network has the capacity to absorb all the power, the price is fixed by the external price, giving no particular incentive to a local flexible load. The SDM should integrate in the external price a part relative to the cost of the grid distribution, in order to give a criteria for the investments needed: choice for grid reinforcement (by DNO) or choice for energy control (by end-users). The need is a balance between these two kinds of investments in order to reach an appropriate level of distribution structure and a better usage of the local electricity (avoiding too much variation and difference between the daily minimal and maximal power flow).
A point shown on extra wind power is the duration of these periods. If the controlled power is low, the energy involved entails large energy storage system (over a day for instance). The thermal storage is a cheap and efficient solution when thermal usage is needed, nevertheless it asks for problems for the other kinds of energy storage.

With the wind characteristics and grid limitations on Oland,. during winter the periods with excess supply typically range over at least a day. The ability to adapt of e.g. residential heating is still not uninteresting here, as there are smaller variations that can be handled by them. But there is a need for e.g. hybrid system loads that are able to tackle the base excess demand. We identified one big such load in the district heating system present in the area. Furthermore we looked at the possibility that there might be industrial load with interesting properties.
With this mix of consumers, and sufficient load that could adapt to variations in local production we see that there is an interesting potential in a local SDM market.

The most straightforward and simple market model that could be evaluated is a single-commodity market, which in this setting is a market where energy bound to a specific hour is treated as an independent good. The bidding behaviour of the wind farms would be exactly the same on such a market as it is on the Consec market of these simulations. This is due to two factors; first the hourly resolution of the market gives an interval that is really long for the wind based production and there is no need for the ability to enter block bids on a Consec market, second the character of wind based production gives that the producers cannot benefit from adaptive bidding either.

On consumer side it is different. We have seen in the simulations (including the LV-cell scenario) that there are consumer categories that are able benefit highly on the bidding opportunities of a Consec market. Some have high flexibility to adapt to variations in supply on the market others have properties that could be expressed in block bids.

Altogether this gives that the Consec market mechanism provides the actors and hence the market with opportunities that cannot be met by a single-commodity market.

It would be to start in the wrong end to say that grid reinforcement would be an alternative to SDM markets when bottlenecks in the power system are dealt with. The truth is that we have presented the SDM concept as an alternative to grid reinforcements in situations when this is to costly and/or other constraints (permissions to build, etc.) make it hard to use grid reinforcement to solve the problem.

The ultimate situation is when good locations for wind production cannot be utilised due to grid capacity constraints. That is, if the alternative to an SDM market is that the wind farm is not built or is reduced in size considerably. A gain of the introduction of a market may be that larger wind farms can be built.

Naturally, if SDM markets are introduced to solve problems related to grid capacity, such as the ones we have based above simulations on the market would not be limited to handling this problem and nothing else. When the market is established it should be used to handle any variations in supply and demand that it is exposed to. Hence, if the cost of extra grid reinforcement and of the introduction of an SDM market solving the capacity problem where comparable, there are arguments for to choose the latter as it is an instrument that potentially could be used to solve more problems.

4.2.3.4 Conclusions

We conclude with a simple statement saying that the work performed on mechanisms for market based SDM and simulations within the CRISP project has given valuable and promising insights. We believe market based SDM being highly interesting for future developments in power systems and dynamic power markets. The concept may be used on local level or covering large power systems. It may be an interesting and novel concept to be used when grid constraints limit the possibilities to develop wind based production – given that consumption with the right properties is present or could be introduced. It may be even more interesting as a means to handle overall fluctuations in supply and demand, and to increase market efficiency.

5. Recommendation and expectations

About the EPS faults simulation, a critical point is evaluating the right contribution of the different types of generation installed in the distribution networks during the faults. A limitation in massive DG insertion may appears due to the induced fault currents, leading to non admissible current constraints in the network equipments and conductors, and leading also to difficulties for the network protection settings. We show in our simulations that the main problem is associated with the synchronous machines that are able to contribute to a temporary to fault. The simulation gives results where the main value for the current is provided by the HV/MV transformer, meaning that DG insertion is not really a problem at the MV scale, compared with the existing situation. Nevertheless on the LV side the problem is quite different: the MV/LV transformer reduces strongly the going-through short-circuit current, the nominal current of local generator may be relatively high compared with the capacity of the transformer (50% for instance), and the protection with fuses involves more sensitive, fast and unexpected reaction (the induction machine may have impacts in these parts of network during faults).
So we recommend strongly to model carefully the distributed generation for studying fault contribution and network protection settings. The protection system has to be correctly modelled also, especially for the LV fuses that will risk to be strongly solicited.

We recommend using such a similar solution as presented in CRISP project for fault localization in MV networks. The solution proposed for fault localization is enough adapted for existing MV networks, and also for future networks including a massive insertion of DG. A main part of these DGs are expected to be installed in LV cells and they should be based on power electronics and induction machines interfaces with the grid.

From an application viewpoint, the consec approach for the market creation lead to multiple lessons as listed below:

- **Bidding opportunities.** The actors on a day-ahead electricity market of today are in principle limited to bidding on each time interval (typically an hour or thirty minutes) even though there sometimes are possibilities to enter bids on blocks of consecutive hours on e.g. the NordPool day-ahead market. With the work presented in this deliverable we show that it is possible to challenge these limitations. With carefully chosen (still restricted) bidding opportunities it is possible to enrich the expressiveness on the market. Assuming that the participants act price takers and that they utilise these opportunities this gives that they are able to express their preferences more truly. Hence we reach a higher quality market outcome compared to markets of today.
- **Electronic agents.** Automated electronic agents are a way to represent small scale actors as well as larger ones on the market. By this the actors them selves need not engage in the (daily or so) market process more than they are engaged in adjusting e.g. a comfort system of today. Much is left for future work when it comes to agent behaviour, but the simulation results are still strong and promising.
- **Simplicity.** It is highly valuable if anyone interested could convince herself that the market outcome for her is “fair” and correct. We believe that the Consec mechanism, even though rather complex in itself, has such properties that the actor can do this. Other alternatives ought to be evaluated from this perspective too.
- **Scalability.** Scalability is a critical issue when it comes to SDM on a larger scale. There are two aspects of scalability, how a mechanism scales in numbers of commodities (here time intervals) and how it scales in numbers of actors. We find the latter the most interesting; as we believe that the interest in running e.g. a market on an hourly scale for with more than a full day is limited. Scalability has not been an issue deal with in the simulations, but we have earlier experience and the basic design of the mechanism that show that that the Consec mechanism scales well in numbers of actors. Hence our experience shows that it is possible to construct electronic SDM market mechanisms that scale well in numbers of actors.
- **Wind farms and similar.** One of our simulation scenarios is based on planned wind farm expansion on the island of Öland, Sweden. The evaluation of the results is highly interesting when it comes to actor characteristics. Some actors have a high flexibility when it comes to short time (hours) variations on the market. A good example is building heating and similar processes. The same actors have more limited possibilities to adapt to longer time (days and more) variations on the market. Here we identified e.g. hybrid systems that can switch between electricity and other fuels for the processes. A conclusion is that

there is an interesting relation between the goal of the SDM market and the characteristics of actors of the market – defining what actors that are the most interesting ones.

- **Market based supply – demand matching.** When constructing and running the simulations we have seen that there are potential actors that have a flexibility that is large relative their demand (supply). Hence, the concept is highly interesting for future development of power markets. The driving force may be grid constraints as in the wind farm simulation scenario, a strive for to limit the interaction between local cells in the grid and higher order cells, or a strive for to counteract fluctuations in total supply and demand as in the LV-cell scenario. We hold the question of what actors to integrate on SDM markets open as this may vary with the goal of introduction of the concept. In some cases only actors with special properties are really interesting (as we have seen in the Öland based wind farm scenario), in others it may be open for anyone to choose to act on the dynamic SDM market, there might even be situations when end users ought to be forced to join such a program.

From computation or communication viewpoint, the consec approach for the market creation lead to the following keypoints:

- **Expressiveness versus complexity.** In an ideal world we would like to be able to let anyone express whatever preference she has on a market such as an electronic SDM market, in practice this is not possible. With both the Consec approach and with the Newton-Raphson styled approach we have shown that it is possible though to extend the opportunities to express ones preferences considerably compared to e.g. today's day-ahead electricity markets.
- **Scalability.** Scalability is a central issue as soon as we want to integrate not only small the actors of small cells within a power grid, but more or less all actors of a large grid – both large scale actors and small scale actors – into a common, possibly multi layered SDM market. The very starting point of the design of the Consec mechanism was that we wanted to continue the work on mechanisms that are applicable to markets with large numbers of participants, a work that started with the CoTree market mechanism for single commodity markets [2]. The design is such that the mechanism scales well to markets with huge numbers of participants, covering e.g. all actors in a national electricity grid. Hence it is possible to construct mechanisms that scale well in numbers of actors.
- **Distributed computations.** Another computational and communicational issue that is central is whether all market computations have to take place at a central spot; that is if all information needed has to be communicated to the same place. Once again the work with the Consec mechanism shows that this need not be the case. It is possible to construct mechanisms and corresponding algorithms that can perform essential parts of the work in the network, when the information is collected (bids) and distributed (information on prices and allocations).
- **Agent construction.** The construction of electronic agents representing actors and translating their preferences into bids on the market is non trivial. We have only been able to construct limited and rough agents within the simulation work. The agents have not been in our main focus (the system and mechanism as such has been) and more emphasis has to be put into these aspects of electronic SDM markets in the future. The challenge is to construct agent interaction on the basis of self interested agents[2] on the market such that they are able to reach their individual goals as well as such that the outcome from a system viewpoint is what we want to achieve. We have reached quite far but as indicated in the main text, there is more to be done on this issue in the future.

6. Conclusion

Various kinds of simulations were performed during CRISP project. This document collected the main information about the simulation, especially the simulation produced with the tools developed in the WP2, for preparing the experimentations. Four main approaches have been reported: the fault diagnosis tool, the robustness index adapted to a large network in case of massive DG insertion, the approach of market mechanism in LV and MV cells and the approach of market mechanism for controlled load and DG with CONSEC.

The function called 'HTFD tool' used as supporting function for the application (managed by a local agent) 'fault detection, isolation and reconfiguration' has been evaluated by simulation. Different studies with loads and DR insertion has been performed. The results show that the solution proposed is interesting even in case of important insertion of DG. A main reason is that the major part of the fault current is always provided from the

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[2] The goal of a self interested agent on the market is only to obtain best possible result for the entity he represents, not to solve any problems on an overall level.

main substations. Even if the current contribution of DR massive insertion becomes an issue (specific case on weak network including a lot of DR), the data used for current measurement can be chosen conveniently to avoid critical inaccuracy of the application. The ICT system may be arranged to collect the data at the first fault cycle, but also at the following second fault cycle after the fast interruption (and the disconnection of the local generators near to the faulty section).

In this way the simulations show that the solution proposed for the future automated application is adequate. The accuracy of the HTFD tool allows the operator to isolate correctly the faulty area, and to have a precise location where to send the field crew.

The CRISP project included simulations on transmission and distribution systems, with a focus on the interface between these two types of networks. The proposed model for transmission has been simulated with different rate of insertion of DG using Eurostag simulator. The DG impacts during major events such as short-circuits, frequency deviation, line tripping or voltage collapse has been studied for robustness purpose. A methodology has been proposed for evaluating a robustness index in a real-time future operation approach. A possible scope is to give technical quantified limitation for DG insertion in the EPS.

It is still difficult to give a value for a limitation rate for DG insertion: this technical limitation is highly dependant on the system analysed (extension of the voltage dip due to critical fault among the interconnected system), on the real distribution of the DG inside the whole interconnected network and on the performance expected for the DG control and protections. Row figures show that 20% DR insertion does not involve heavy problems, 50% DR insertion may induce a high level of traditional power reserve to face critical situations if there is no improvement on the DR control (contribution to ancillary services) and DR protection (setting robustness and sensitivity to allow nuisance tripping).

The market mechanism studied at local scale has been called the PowerMatcher, the main aspect being a fine controlled balance between production and consumption. The concept of bidding process is presented with a set of rules for maintaining the market system stable from day to day. The simulations presented show possible stable optimization when matching the power. The less expensive power is exchanged, with ultimate price deviation in the two directions (up and down). The typical result is a converging bid for the local price during the next time period (from a few tens of minutes to several hours), and a return back volume and validated price for the producers distributed among the network. The concept of market cell is applicable since enough detail is kept from stage to stage for bidding needs. The tool gives an interesting illustration of the possible future electric market, with price natural incitation to converge through a flat production and consumption daily curve.

The 'consec' approach used for simulating a market mechanism including different types of controlled loads has been investigated. The response of the local demand with identified typical loads (as large heating system) and with intermittent producers (as large wind power plant) shows that real time pricing is able to deal with local technical temporary constraints (in the order of a few minutes to a few hours). As in the previous paragraph the pricing strategy has limitation impacts and variations caused by the existing surrounding network that brings minimum and maximum price. The local market mechanism has been illustrated in a specific case: island of Öland in the south of Sweden, taking into account a limited technical transmission capacity, large local and addressable industrial loads and large wind power plants. The simulations show that the price may be used as a time controlled signal to achieve global (at the scale of the cell) mitigation of possible high load variations, in order to reach normal power exchange in the lines between the continent and the island. The need for such a system may depend on the season due to the weather (temperature or wind condition for instance) and the local activity (a lot of tourists during the summer for instance) that induces or not technical constraints on the local network. The difficulties expected are about the need of new transmission and distribution capacity (lines of 50kV and distribution lines among the island) to face local high increase of demand and production. The local market may help to differ or reduce the planned work of capacity installation without any control on the loads and on the production.